# 24 Energy Efficiency: Comparison of Different Systems and Technologies

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Wei-Yin Chen, John Seiner, Toshio Suzuki & Maximilian Lackner (eds.), *Handbook of Climate Change Mitigation*,
DOI 10.1007/978-1-4419-7991-9_24, 

**Abstract:** The efficient use of energy, or energy efficiency, has been widely recognized as an ample and cost-efficient means to save energy and to reduce greenhouse gas emissions. Up to one third of the worldwide energy demand in 2050 can be saved by energy efficiency measures. In this chapter, several important aspects of energy efficiency are addressed. After an introduction and definition of energy efficiency, historic development, state-of-the-art, and future trends of energy efficiency are presented in the light of life cycle assessment and total cost of ownership considerations. Energy efficiency in various sectors, viz. energy production, energy transmission and storage, transportation, industry, buildings, appliances, and others, is reviewed. Concurrent measures such as recycling or novel materials are also discussed and touched upon. Energy conservation is covered in the final section of this chapter. References for deeper study are provided with an emphasis on guidelines on how to improve energy efficiency. Given the breadth of the subject, only exemplary coverage can be aimed for. The purpose of this chapter is to highlight the significance of energy efficiency and to provide cross-learnings from achievements in different sectors so that energy efficiency in the readers' own facilities and installations can be assessed and improved with cost-effective means as a contribution to climate change mitigation, cost savings, and improved economic competitiveness.

## Introduction

Energy stands for a range of commodities, for instance, thermal or electrical. It is a scalar physical quantity and can be defined by the amount of work that can be done by a force. Energy comes in different forms: Classical mechanics distinguishes between kinetic and potential energy. In the everyday world, one can see chemical, thermal, gravitational, light, and electrical energy, to name but a few. These forms of energy can be transformed into each other. The SI unit of energy is joule (J), with other common units being kilowatt hour (kWh), ton of oil equivalent (toe), and British thermal unit (Btu or BTU).

$1 \text{ J} = 1 \text{ kg/m}^2/\text{s}^2 = 1\text{Ws}$
$1 \text{ kWh} = 3.6 \times 10^6 \text{ J}$
$1 \text{ toe} = 41.868 \text{ GJ} = 11{,}630 \text{ kWh}$
$1 \text{ btu} = 1.060 \text{ kJ}$; $1 \text{ Quad} = 10^{15}$ (1 Quadrillion) $\text{btu} = 1.06 \times 10^{18} \text{ J}$

The worldwide energy consumption is on the order of 500 exajoules ($5 \times 10^{20}$ J) per year, which corresponds to an average consumption rate of 15 terawatts ($1.5 \times 10^{13}$ W). Energy efficiency, i.e., the efficient use of energy, describes the use of less energy to achieve the same level of energy service. Energy efficiency is a universally applicable concept relevant for consumers and industry alike. It can be achieved by a more efficient technology, an improved process, or a change of individual behavior. Obstacles toward the introduction of energy efficiency are often not imposed by technical or economic reasons, but rather by the habits, norms, and mindset of our social institutions, often termed "market barriers." Therefore, apart from increasing research and development (R&D) to create and improve energy-efficient technologies and appliances, one has to address the

issue from other angles such as policy making [1], too. The proliferation of energy-efficient technologies requires stimuli outside the scope of technical, and economic, logic arguments.

Also, it has to be noted that the proliferation of technically and economically superior technology is a gradual one [2]. Subsidies can have an important effect on the penetration rate of new energy technologies [3], as can industry agreements [4]. In its most current World Energy Outlook [5], released in autumn 2009, the International Energy Association (IEA) has compared the "reference scenario," a kind of baseline or BAU (business as usual) scenario, to its suggested course of action to control climate change, which is termed "450 scenario" (discussed below). In the reference scenario, worked out for the period of 2010–2030, the world is set for a rise in temperature of up to 6°C, leading to severe global challenges in terms of irreversible environmental damage and energy security. The notion that energy security can be an issue has existed since the OPEC oil embargo of 1973 (otherwise known as the oil crisis), followed by the second energy crisis 6 years later. It was recently revived in Central Europe in the winter of 2009 [6, 7]. Globally, crude oil prices, exceeding for the first time 100 USD per barrel in the same year, have also led to concerns about energy security in terms of affordability and sustainability. There is no straightforward definition for energy security. In [8], indicators based on availability, accessibility, affordability, and acceptability were created. With depleting fossil fuel sources and concentration of these in fewer regions, not all of which are considered politically stable, it can be anticipated that fossil fuel prices will go up and will fluctuate more strongly, partly driven by speculation. Today, the world relies to 80% on fossil fuels for primary energy production.

Within the 20 years considered by the IEA, the worldwide energy demand is predicted to increase by 40% based on today's level. The "450 scenario," in which the concentration of greenhouse gases in the atmosphere has to be kept below 450 ppm $CO_2$ equivalent, would only lead to a temperature increase of 2°C compared to preindustrial times (because other greenhouse gases such as $CH_4$ and $N_2O$ have different greenhouse warming potentials [GWP], they are expressed in $CO_2$ equivalents for easier comparison, see later). That IEA "450 scenario" demands for fossil-fuel consumption to peak by 2020 and for energy-related $CO_2$ emissions to be cut from 28.8 Gt in 2007 to 26.4 Gt in 2030 [5]. In the reference scenario, the world's primary energy demand grows by 1.5% per year from 2007 to 2030, compared to 0.8% per year in the "450 scenario." The two scenarios are depicted in *Fig. 24.1*, reprinted from [5].

As it can be seen from *Fig. 24.1*, the largest contribution to $CO_2$ abatement – more than half of total savings – can be made by energy efficiency measures of end-users. One half (2030) to two thirds (2020) [5] of the total required $CO_2$ reduction can be achieved with energy efficiency. Another strong contribution comes from changes in the mix of power generation technologies. The reference scenario, by contrast, assumes 1,000 ppm of $CO_2$ equivalent in the atmosphere.

*Table 24.1*, based on [5], shows the worldwide energy-related $CO_2$ emissions. Similar results, focused on the USA, were found in [9]. As a conclusion, one can say that energy efficiency has a huge potential. In this chapter, several aspects of energy

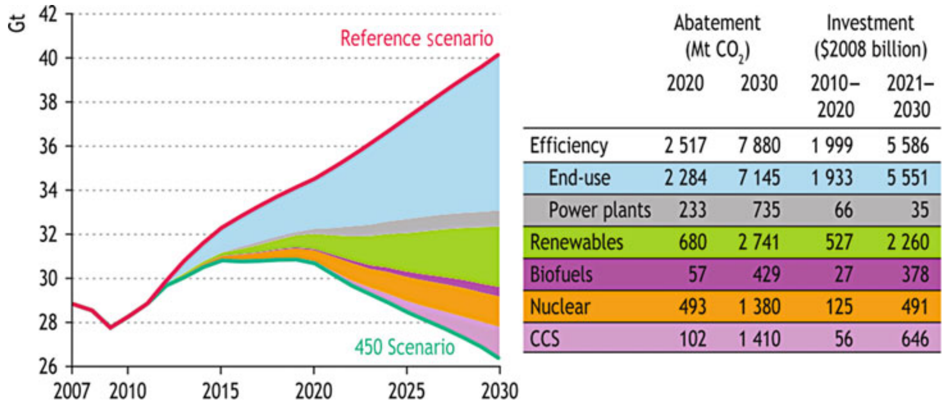



**Fig. 24.1**

**Global $CO_2$ emissions in the "reference scenario" and in the "450 scenario" in the 2009 World Energy Outlook of the IEA. The table on the right provides the estimated figures for $CO_2$ emission abatement and the required projected investments needed to achieve the "450 scenario." While one fifth of the $CO_2$ reduction in 2020 stems from renewables, two third can be attributed to energy efficiency measures (Reprinted from [5] with permission from OECD/IEA)**

**Table 24.1**

**Global $CO_2$ emissions in the "reference scenario" and the "450 scenario" in the 2009 World Energy Outlook of the IEA, compare** *Fig. 24.1* **[5]**

| $CO_2$ emissions | 1990 | 2007 | 2030, reference scenario | 2030, 450 scenario |
|---|---|---|---|---|
| Total | 20.9 Gt | 28.8 Gt | 40.2 Gt | 26.4 Gt |
| Per capita | 4.0 t | 4.4 t | 4.9 t | 3.2 t |
| Power generation | 36% | 41% | 44% | 32% |
| Transport | 22% | 23% | 23% | 29% |
| Industry | 19% | 17% | 15% | 17% |
| Buildings | 14% | 10% | 8% | 10% |
| Others | 10% | 10% | 9% | 11% |

efficiency for climate change mitigation are highlighted. Complete coverage of the topic cannot be provided within the scope of this chapter, so a selection has been made to present some of the most relevant areas related to energy efficiency.

## What Is Energy Efficiency

Energy efficiency is, as the term implies, the efficient use of energy, i.e., using a lower amount of energy to achieve the same level of energy service [10]. It can be achieved by improved behavior or by more efficient technology.

Thermodynamics teach that energy can only be transformed. According to the First Law, energy can neither be created nor destroyed. A change in the internal energy of a system, $U$, can be achieved by adding heat $Q$ or work $W$:

$$\mathrm{d}U = \mathrm{d}Q - \mathrm{d}W \tag{24.1}$$

where $\mathrm{d}Q$ and $\mathrm{d}W$ are incremental changes in heat and work, respectively (the minus denotes that positive work is being done by the system). Equation 24.1 can be rewritten as

$$\mathrm{d}U = T\mathrm{d}S - p\mathrm{d}V \tag{24.2}$$

where the work done by the system while expanding is $p\mathrm{d}V$. The amount of heat added to the system can be described by $\mathrm{d}Q = T\mathrm{d}S$ with $T$ being the temperature and $S$ the entropy. In a heat engine, thermal energy is converted to mechanical energy by exploiting a temperature gradient between a hot and a cold reservoir for an energy transfer. The efficiency of such a heat engine is given by the ratio of useful power to heat energy input. It can be derived as follows:

$$\mathrm{d}W = \mathrm{d}Q_\mathrm{c} - (-\mathrm{d}Q_h) \tag{24.3}$$

$\mathrm{d}W = -p\mathrm{d}V$, i.e., the work done by the engine $Q_\mathrm{h} = T_\mathrm{h}\mathrm{d}S_\mathrm{h}$, i.e., the heat energy taken from the high-temperature reservoir $Q_\mathrm{c} = T_\mathrm{c}\mathrm{d}S_\mathrm{c}$, i.e., the heat energy delivered to the cold temperature reservoir. In the reversible Carnot heat engine cycle ($\mathrm{d}S_\mathrm{c} = \mathrm{d}S_\mathrm{h}$, i.e., no net change in the entropy), the maximum efficiency is

$$\eta_{\max} = 1 - \frac{\mathrm{d}Q_\mathrm{c}}{\mathrm{d}Q_\mathrm{h}} = 1 - \frac{(T_\mathrm{c}\mathrm{d}S_h)}{(-T_c\mathrm{d}S_h)} = 1 - \frac{T_c}{T_h}. \tag{24.4}$$

The Carnot efficiency is a theoretical one because it considers an infinitesimally small temperature change. As for "real" heat engines, such as internal combustion engines or power plants, one is typically after a sizeable power output, which is an irreversible process. Therefore, the ideal, reversible Carnot process does not well describe the efficiency of a technical system. Taking the concept of endoreversible thermodynamics [11] into consideration, the efficiency of a heat engine operating in irreversible mode can be obtained as

$$\eta = 1 - \sqrt{\frac{T_\mathrm{c}}{T_\mathrm{h}}} \tag{24.5}$$

This expression is known as the endoreversible efficiency or Chambadal–Novikov efficiency [12, 13]. It allows a more realistic estimation of the efficiency of a heat engine, which can be termed semi-ideal. The endoreversible efficiency takes the destruction of *exergy* in an irreversible process into consideration. Exergy is the highest possible useful work during a process that brings the system into equilibrium with a heat reservoir [14–18]. It was introduced by Gibbs as a special form of the Gibbs available energy. Exergy is the *work potential* of a system; it can be potential (gravitational or magnetic force field), kinetic (velocity), physical (pressure, temperature), or chemical (composition) [15]. Exergy analysis can be used to determine inefficiencies.

**Table 24.2**

**Efficiencies of power plants [19, 20]**

| Power plant | Technology | $T_c$ (°C) | $T_h$ (°C) | $\eta$ (Carnot) | $\eta$ (Endoreversible) | $\eta$ (Observed) |
|---|---|---|---|---|---|---|
| A | Coal-fired | 25 | 565 | 0.64 | 0.40 | 0.36 |
| B | Nuclear power | 25 | 300 | 0.48 | 0.28 | 0.30 |
| C | Geothermal power | 80 | 250 | 0.33 | 0.178 | 0.16 |

*Table 24.2*, compiled from [19, 20], compares the Carnot and Chambadal–Novikov efficiencies to the actual ones of three power plants. From the above table, it can be seen that the endoreversible efficiency predicts the observed one well. In [21], theoretical efficiency limits for energy conversion devices are reviewed.

The combination of energy efficiency and renewable energy is often referred to as "sustainable energy." Sustainability was defined in 1983 by the UN World Commission on Environment and Development as follows: "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*"

"Energy productivity," similar to energy efficiency, has a narrower scope. Another aspect related to energy efficiency in the context of climate change mitigation is the concept of *greenhouse gas emission factors.* Apart from $CO_2$, other greenhouse-active gases can be emitted, such as $CH_4$, $N_2O$, or halocarbons. Reference [22] provides an overview.

There is a huge potential for energy efficiency improvements. Three recent studies on this topic are [23] and [9], making projections until 2020, and [5], which extends its forecasts to 2030. It needs to be stressed that such impressive potentials can only be turned into reality if significant initiatives are launched. Program costs have to be catered for, too. Different approaches to measure energy efficiency in industry are shown in [24]. Indicators of energy efficiency are discussed in [25] and [26]. Another important consideration in energy efficiency is the entire life cycle of a product. *Life-cycle energy efficiency* [27] not only considers actual use of a piece of equipment but also its production and disposal (see section on "Life Cycle Assessment (LCA)" later). *Energy efficiency trading* can only be mentioned here. It is discussed in [28]. A detailed overview on energy efficiency is provided in [29].

## Significance of Energy Efficiency

There is – unfortunately – no such thing as a perpetuum mobile. As a consequence, energy can only be transformed from one form into another one, which happens under certain losses (see also above). Users of mobile phones, notebooks, and any other mobile device

will naturally and subconsciously appreciate energy efficiency – because energy is obviously a scarce resource in these applications. Service life and hence usefulness will depend on the efficiency and energy density of the gadget [30]. However, energy efficiency is a much broader topic.

Energy is the leading source of anthropogenic greenhouse gas emissions, approximately 65% [5], and hence needs to be at the core of climate change mitigation actions. In the IEA's reference scenario, the global energy demand is set to increase by 40% from 2007 to 2030, reaching 16.8 billion toe [5]. Ninety percent of this increase is predicted to happen in non-OECD countries, with India and China accounting for half [5]. Global electricity demand is projected to grow by even 76% from 2007 to 2030, requiring 4,800 GW of additional capacity. This is five times the existing US capacity [5].

In the proposed course of action, the "450 scenario," more than 50% of all (necessary) energy savings are realized by energy efficiency measures. The target is an energy-efficient and low-carbon economy. By 2050, energy efficiency measures could cut the total worldwide energy consumption by as much as one third [5].

Energy efficiency has a large scale effect. Apart from addressing global warming, energy security and fossil fuel depletion are tackled alongside solid savings for individuals, enterprises, and nations at large. Air quality, particularly in urban areas and in developing countries, can also be improved by energy efficiency measures. There are other environmental co-benefits, too, from implementing energy efficiency measures.

By focusing on energy efficiency rather than on increasing energy production, a cost-effective, "soft" energy path is followed. The term "negawatt" was coined two decades ago to describe electricity that "was not created due to energy efficiency" [31]. Energy efficiency has been widely recognized as a vast, low-cost energy source [9]. The reason why this unused potential is so large stems from the multitude of barriers that impede energy efficiency today [2, 9, 32]. Unlike the production factors of labor and capital, which have seen impressive optimization since the industrial revolution, energy is far from being at the lowest possible level.

Energy efficiency has become part of the political agenda in many countries [33]. Monitoring energy intensity is common practice since the 1973 oil crisis. How policies can increase energy efficiency is shown in [34] for the OECD countries (OECD = Organization for Economic Co-operation and Development; 34 member countries, which are considered highly developed) and in [35] for the state of California, a leading region for energy efficiency as will be referred to in this chapter of the handbook.

For corporations, energy efficiency is an important pillar for the "triple bottom line," i.e., their performance in economic, social, and environmental aspects. Businesses and consumers alike start taking energy considerations into account for decision making. It is estimated that energy is a strategic factor for 40% of all global revenue [36]. Unpredictable volatility in fuel prices, driven by depletion of crude oil and speculation, places a burden on companies and economies as a whole, which they feel needs to be controlled. Reference [37] provides an overview on the economic aspects of climate change. With energy efficiency being the easiest way to save energy, it is highly relevant to mitigate climate change effects and their detrimental consequences.

## Benefits of Energy Efficiency

Energy efficiency offers several direct and indirect benefits, some of which are obvious. The reduction of pollution and greenhouse gas emissions aids the environment. For businesses, reduced energy bills will translate into competitive advantages. Also, energy efficiency measures can lead to higher worker productivity and reduced sick-leave rate [9] as concurrent benefits. Consumers can enjoy increased comfort levels [2], particularly those living in low-income households. Indirect benefits, as an example, are also related to health (less drafty and damp rooms after the implementation of energy efficiency measures in private homes such as insulation upgrading). As a nation, a key benefit is an improvement in energy security, another one the reduced exposure to volatility in energy prices. There has also been a wide discussion on job creation by the quest for energy efficiency. While it is true that energy-intensive production processes are shifted toward developing countries, leading to job losses in countries of the European Union and the USA, for instance, there should be a net positive effect from the job market stimuli provided by energy efficiency. For instance, the market for building insulation is estimated at $10–12 billion for the USA alone [9].

An overview on the market size for energy efficiency in the USA is provided by [38].

Some considerations on actual and potential job creation by energy efficiency improvement programs are provided by [9], where the potential for the USA is estimated to lie between 600,000 and 900,000 jobs over the next decade in direct, indirect, and induced jobs. A national commitment to green buildings has the potential to generate 2.5 million and to support 8 million American jobs [39], with similar prospects being offered in other countries. The job market potential of clean energy is reviewed in [40].

Energy efficiency will not be the sole solution. There will still be a need for new, additional power plants, partly to meet increased demand, partly to replace old ones. Also, there might be additional demand that is now unaccounted for, e.g., to power electric vehicles [9] that are likely to replace traditional cars to some extent.

## Downside of Energy Efficiency

While energy efficiency as such is indisputably a good thing, there are several aspects that have to be considered to avoid detrimental overdoing. First, the *economics* have to be considered. In a competitive landscape, corporations will only implement energy efficiency measures that "pay for themselves" (see also later). High upfront investments are one of the barriers toward better energy efficiency. Apart from costs, *complexity* is another aspect to consider. In order to improve the efficiency of a plant or an engine, advanced control systems are required, which need to be maintained. Capable technicians and additional resources have to be provided to that end. The most economic process might not be the most reliable one. As *operability* of technical equipment, particularly in the capital-intensive process industry is of utmost importance, some concessions to energy efficiency are sometimes well accepted from a process point of view. For many production

plants, 1 day of additional, unplanned shutdown per year will mean the difference between profit and loss. Also, plant personnel might focus on other aspects than energy efficiency when operating a unit or equipment [41] to safeguard "trouble-free" operation, or simply be too busy to concentrate on continuously optimizing energy usage. Another extreme, hypothetic example of an inefficient energy saving attempt would be a person having an accident at home because of not turning on the light when fetching something from the cellar or during night. For these reasons, it might happen and even be advisable not to squeeze out the last bit of energy efficiency from a given system, but rather to act with commonsense.

## Energy Efficiency versus Energy Demand: The Rebound Effect

The effect that energy efficiency improvements on the micro level (i.e., machines and individual plants in industry) do not fully translate into the expected energy savings on the aggregate level (such as the economy) is termed "rebound effect" or "Jevons' paradox." It is also called the *Khazzoom–Brookes postulate*. The rebound effect can be direct or indirect. If it is >100%, it is called "backfire" [42]. Simply put, energy efficiency makes energy services cheaper, so demand tends to increase. This concept is called "elasticity of demand." A more economic car might tempt its owner to driver faster and further, thus partially offsetting potential energy savings. A car producer can decide to install more electronic devices for increased driver comfort in a car that has been made more fuel efficient thanks to the use of lightweight construction materials and a better engine.

The extent of the rebound effect depends on the elasticity of demand, which tends to be stronger with consumers than with industrial plants [42]. William Stanley Jevons studied the rebound effect during the industrial revolution [42]. In his 1865 book "The Coal Question" [43], he was pondering over the question whether efficiency measures would really lower actual coal consumption, based on empirical evidence that after efficiency improvements with steam engines and in steel production, the actual energy consumption had soared. For more information, see [44, 45].

## Energy Intensity

Intensity is an ambiguous term. In physics, it is power per unit area ($W/m^2$), a time-averaged energy flux. In heat transfer, intensity commonly denotes the radiant heat flux per unit area per unit solid angle ($W/m^2/sr$).

Here, energy intensity is an economic concept as a measure of the energy efficiency of a nation's economy. It is calculated as units of primary energy consumption per unit of GDP (gross domestic product) or value added, measured in (MJ/$) or (toe/$). The energy intensity of a country is influenced by many factors, for instance, the climate. Economic

productivity and standards of living contribute as well as the energy efficiency of buildings and appliances, traffic patterns (public transportation vs. individual cars), and the way energy is being produced [46].

Energy intensity can hence be used as a surrogate for aggregate energy efficiency. Countries differ strongly by energy intensity, and within countries, there are marked differences amongst regions. In the USA, a state with superior energy efficiency performance is California, which has established leadership in, e.g., per capita energy consumption [47, 48]. The energy efficiency of different countries is assessed in [49]. The term "energy intensity" can also be applied to a production process as a synonymous expression for specific energy consumption, based on quantity (kg) or value added ($) or (€) (see also section on "Energy-Intensive Industries").

## Emission Intensity (Carbon Intensity)

Another concept is the emission intensity. It is the average emission rate of a given pollutant from a given source related to the intensity of a specific activity, e.g., grams of $CO_2$ per megajoule of energy produced (g/MJ). The term emission intensity is often used interchangeably with "carbon intensity" and "emission factor" in the climate change discussion. Other greenhouse gases and pollutants can be considered, too, by calculating $CO_2$ equivalents. *Table 24.3* provides an overview on emissions intensities, compiled from [50].

The subscripts in *Table 24.3* stand for "thermal" and "electric." In combined heat and power (CHP, cogeneration), both heat and power are produced from a combustion process, boosting overall efficiency (see later).

## Historical Development of Energy Efficiency

A proverb says "Things that cost nothing have little value." In this sense, as long as easy access to energy is available, there are few incentives to use it wisely. History tells several lessons here. Visitors to Greek islands will witness testimony of one such unsustainable

**Table 24.3**

**Emission intensities [50]. The ratio of H/C is 4 in natural gas, which is higher than in oil and especially coal, leading to lower $CO_2$ emissions per kWh**

| Fuel/resource | Thermal g($CO_2$-eq)/$MJ_{th}$ | Electric g($CO_2$-eq)/$kWh_e$ |
|---|---|---|
| Coal | 88–94 | 863–1,175 |
| Oil | 73 | 893 |
| Natural gas | 51–68 | 587–751 |
| Nuclear power (U) | | 60–65 |
| Hydroelectricity | | 15 |
| Photovoltaics | | 106 |
| Wind power | | 21 |

practice exercised several thousand years ago, i.e., chopping down trees to build ships without reforestation. There are countless other examples of unsustainable acts related to resource and energy efficiency in the past, some of which have even led to the extinction of a local human population [51]. The global oil crises in the 1970s were a series of events that have triggered several measures for energy efficiency on a large scale, e.g., the creation of the DoE (Department of Energy) in the USA. In the following decade, when crude oil prices went down again, there was reduced motivation to focus attention on energy efficiency in many areas. The industrial sector has improved its energy efficiency continuously over the last 30 years, partly in order to reduce variable production costs and to improve competitive advantage (one also has to take into account that a significant part of energy-intensive production facilities was transferred to low-labor-cost countries in, e.g., Asia). Economic growth, a trend toward increased personal mobility and toward larger homes and the use of more and more appliances, amongst others, has led to a steady increase of absolute energy demand in most industrialized countries.

As a result, the overall energy intensities in the USA have declined as follows between 1980 and 2005 [9]:

Residential sector: −11%
Commercial sector: −21%
Industrial sector: −42%

While the national per-capita energy consumption in the USA has grown by 1.3% per year from 1977 to 2007, which means a doubling, it remained almost constant in California. In the EU, the average efficiency of gas-fired power plants has increased from 34% in 1990 to 50% in 2005, and is expected to increase to 54% by 2015 [52]. For coal-fired power plants, the efficiency, also based on the lower heating value, went up from 34% in 1990 to 38% in 2005 and is expected to increase to 40% by 2015. These trends are visualized in ➋ *Fig. 24.2* below.

As the developed world has built its industry, specific energy consumption was constantly improved. Yet the largest share of historic and current global emissions comes from developed countries. Many people now fear that while other countries race through their development, they might expel "their share," i.e., high amounts of pollutants, into the atmosphere. China, for instance, has been able to maintain economic growth of greater than 9% from 1980 to 2000, while the energy demand only increased by 3.9% per year [53]. This shows that energy demand does not necessarily have to outpace economic growth during the early stages of industrialization and development [53].

A word of caution: Many scientific publications, as well as the public opinion, believe in decreasing energy intensity over time. This hypothesis is often only an assumption, which needs to be proven. In [54], the authors conclude that many energy efficiency trends on a national level follow a stochastic nature, see ➋ *Fig. 24.3* below.

In [55], historic developments and future trends of energy efficiency are discussed. Megatrends [56] will also have an impact on energy efficiency. How they are perceived can differ strongly [57]. In general, there have been marked improvements in certain areas with respect to energy efficiency, some of which were countered, though, by rebound effects.

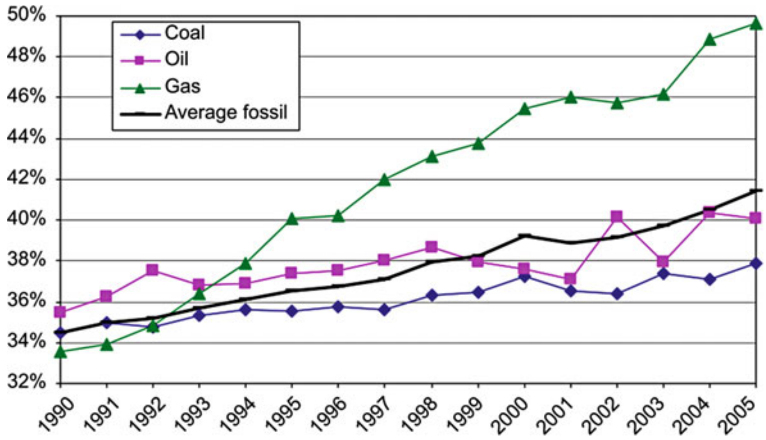



**Fig. 24.2**

**Energy efficiency trends of fossil fuel combustion in the EU27 (Reprinted with permission from Elsevier from [52])**

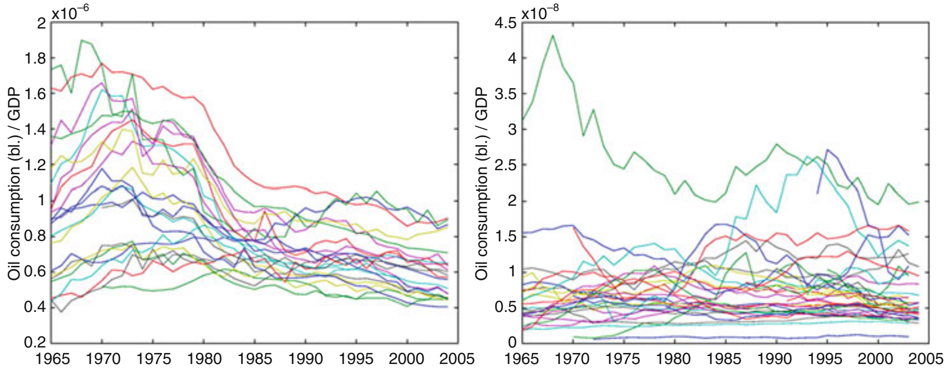



**Fig. 24.3**

**Stochastic movement of energy consumption. *Left*: Oil consumption per unit of GDP for OECD countries from 1965 to 2005. *Right*: Same data for non-OECD countries (Reprinted with permission from Elsevier from [54])**

## Assessing Energy Efficiency Improvements

Energy efficiency improvements can be achieved by technological progress or by changes in behavior. They can be measured. However, for a correct assessment, the following factors have to be taken into account:

- Erosion of part of the improvements by the rebound effect (see above)
- Comparability of data (same year, same boundary conditions)
- Selection of a proper baseline

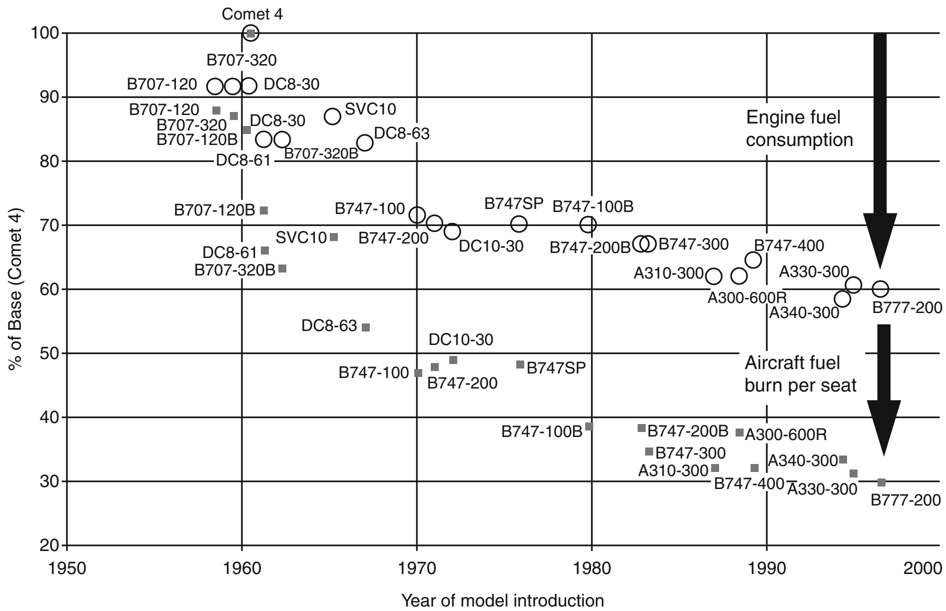



**Fig. 24.4**

**Fuel efficiency of commercial aircraft over the last 50 years. See text for details (Reprinted with permission from [58])**

The baseline for measuring energy efficiency is of utmost importance to avoid wrong conclusions. This is elaborated with an example from the transportation industries below, viz. the fuel consumption of aircraft over time. *Figure 24.4* shows a data compilation of how fuel efficiency of commercial aircraft was improved over the last decades.

Taking the Comet 4 as a baseline, fuel efficiency was reduced by 70% in modern aircraft. Approximately 40% of the improvements are attributed to engine efficiency improvements, and 30% to airframe efficiency improvements [58]. The *de Havilland Comet* was the world's first commercial jet airliner [59].

*Figure 24.4* was taken from an IPPC report. The IPCC (*Intergovernmental Panel on Climate Change*) is a renowned, scientific intergovernmental body established to evaluate the risk of climate change caused by human activity [60]. It was awarded the 2007 Nobel Peace prize together with Al Gore. In [61], the authors argue that the pre-jet era was ignored in the above IPCC discussion, and that the Comet 4 is an unsuitable baseline. From the conclusions of that report [61]:

- The later piston-powered airliners were at least twice as fuel-efficient as the first jet-powered airliners; If, for example, the last piston-engine aircraft of the mid-fifties are compared with a typical turbojet aircraft of today, the conclusion is that the fuel efficiency per available seat-kilometre has not improved. . ..The last piston-powered aircraft appear to have had the same energy efficiency per available seat-kilometre as average modern jet aircraft. The most modern jet aircraft (such as the B777-200 or B737-800) are slightly more efficient per available seat-kilometre.

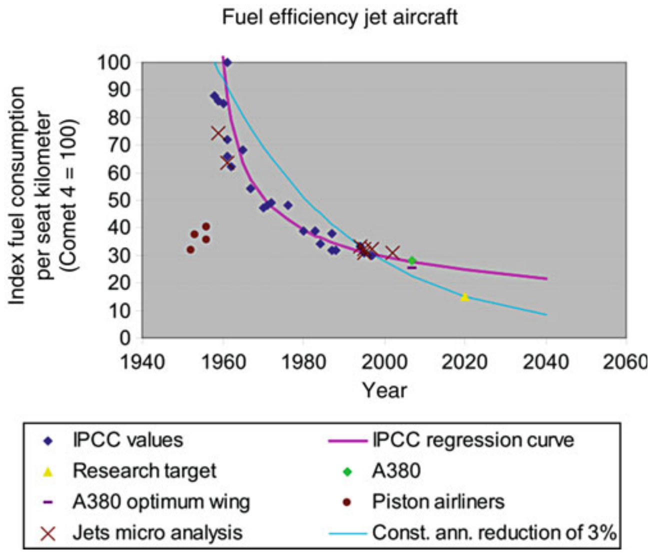



**Fig. 24.5**
**IPCC graph with additional data (Reprinted with permission from [61])**

The findings from this study are depicted in *Fig. 24.5* below. As it can be seen from *Fig. 24.5*, slight changes in the assumptions will lead to strong deviations in the results. This has to be borne in mind when assessing and comparing energy efficiency studies presented by various interest groups.

## Innovation and New Technologies for Energy Efficiency

In order to increase energy efficiency, innovation [62] is needed. By innovation, either of the following energy efficiency improvements can be achieved:

- Carrying out the same task or process with less energy
- Utilizing the same amount of energy to produce more output or higher value
- Redefining the task or process so that the new way consumes less energy

Innovation can take place in incremental steps, or in a disruptive way, when a new technology is developed, for instance. The electric light bulb, being condemned as energy inefficient today, was one such disruptive innovation, which has been around for more than a century. So in order to innovate, engineers and researchers might be tempted to search and build more knowledge in their own area of expertise, and to innovate as much as possible in their very own fields. This strategy has proven successful – take the famous Bell Labs [63] as an example. Fifty years ago, the Bell Labs were generating every new technology that the telephone business needed, and the telephone business, in turn, was using all of Bell Labs' innovations. Bell Labs were virtually unbeatable. However, the rules

of innovation have changed somehow over time. The Bell Labs invented the transistor, which clearly is one of their greatest discoveries. However, Bell Labs did not recognize the value of the transistor, and they gave it away for little money. The transistor, hence after, was extremely successful, but with the main use not being in the telecommunications industry. On the other hand, the very innovation that revolutionized the telecommunications industry – the fiberglass cable – was developed outside that industry. This phenomenon has been observed in many industries over the last 50 years [64] – the major innovations with the biggest impact for an industry are not likely to come out of the industry itself, but will rather be "born" in a different area.

The significance of this development for the realm of energy efficiency is as follows: Energy efficiency can be improved in many ways. In a passenger car, for instance, an improved engine, lightweight plastics components instead of steel, or tires causing less rolling friction will all serve the same final purpose of energy efficiency.

Innovation takes time until its full potential is being realized, though. In [3], the market penetration rates of new energy technologies were studied. It is concluded there that the time for a takeover of market share from 1% to 50% varies from less than 10 years to 70 years, with takeover times below 25 years being associated with end-use technologies. Long investment cycles render the energy production industry inert to change.

## Typical Energy Efficiencies

The energy efficiency of photosynthesis is on the order of 1%, with a fraction of approximately 0.2% being stored as biomass. Sugarcane exhibits peak storage efficiencies of up to 8% [100]. The first steam engines, designed as external combustion engines, had efficiencies on the same order of magnitude.

To visualize the energy balance, i.e., the energy efficiency, of a process or machine, a Sankey diagram can be used. For exergy, Grassmann diagrams [65] are deployed (though both terms are sometimes used interchangeably in the literature).

An example for a Grassmann diagram for nitric acid production is shown below in ➲ *Fig. 24.6* [65].

The Grassmann diagram can be seen as an energy flow diagram, visually explaining which fraction of the total, initial energy ends up in the final product. In order to obtain typical energy efficiencies, or reference energy efficiencies, a benchmark is deployed. The benchmark in energy efficiency is given by the state-of-the-art and so-called BAT (best available technology) values. However, BAT values are often difficult to obtain as corporations tend to keep them secret and patents do not always provide full disclosure.

The energy efficiency and carbon intensity of a given process depend on the system boundaries that are considered, and on the energy path. For instance, whether electricity for a hybrid car has been produced in a coal-fired power plant or by solar cells will heavily impact the overall efficiency (see also "Life Cycle Assessment" and well-to-wheel efficiency, later).

*Actual efficiencies* will depend on a large number of factors such as the condition of a given system or appliance. Examples are the load of an engine, maintenance on motors,

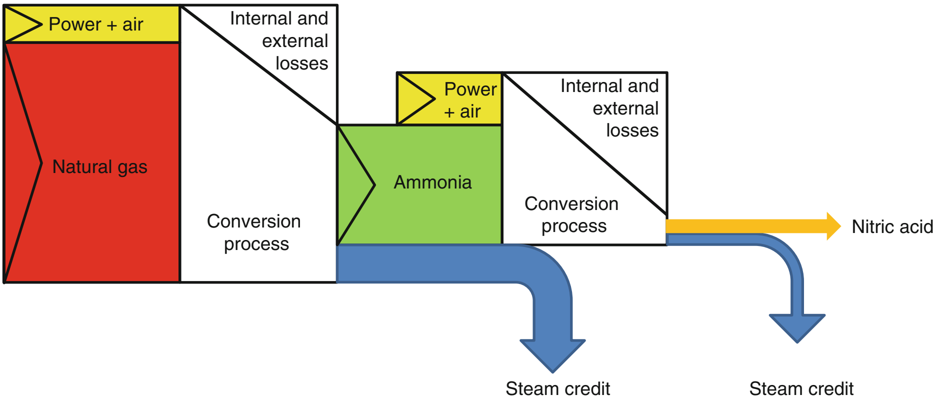



**Fig. 24.6**
**Simplified Grassmann diagram for the production of nitric acid [65]. Reproduced by permission of the Royal Chemical Society (RCS).**

and usage patterns. This is obvious for every car owner who wants to reach the "official" fuel consumption of her car. When energy efficiency potentials are presented in the literature, one has to be careful not to overestimate or mix up the various potentials, which are:

- Technical potential
- Economic potential
- Maximum achievable potential (considering factors such as demographics, market conditions and regulatory factors)
- Realistic achievable potential (taking historic data into account)

People adapt to change at different rates. Take popular technologies as an example. Even for microwave ovens and mobile phones, it took 10–15 years for market penetration. Therefore, the realistically achievable potential is never equal to the full technical potential. Also, the effort to obtain a large part of any potential saving will increase along the way.

For energy efficiencies of various technologies, processes, and appliances, the reader is referred to the respective chapters of this handbook and to the specialized, referenced literature.

## Benchmarking of Energy Efficiency

There are no useful reference data for absolute energy efficiency from a thermodynamic or theoretical point of view. Rather, one can only compare a given process or technology route, device, or method to other solutions in the lab or in the field so that the best available technology (BAT) or state-of-the-art can be determined empirically. Such a benchmarking exercise focused on energy efficiency will yield interesting results.

In [66], for instance, it was found that the energy efficiency of the steel-making plants in several countries was 25–70% above the best plant. In the cement industry, the average was 2–50% higher than the very best plant energy efficiency.

Benchmarking can be used by operators of industrial plants to compare their energy efficiency, and ultimately their competitiveness, to that of their contenders. Consumers can use relative indications of energy efficiency, such as the Energy Star® label, to easily spot energy-efficient appliances as a guide for purchase decisions. It needs to be mentioned that comparing like with like is crucial. If, for instance, steel making plants in two countries are to be compared, sectoral differences must be taken into account [66] (if, for example, there is plenty of secondary steel available, energy efficiency will "automatically" be better). Also, regional differences in feedstock quality [67] or climatic conditions will affect the energy efficiency of a given plant. More information of reliable reference data for energy efficiency comparisons on a national level can be found in [68]. In mature industries, energy efficiency differences from plant to plant are not expected to be very large because improvements tend to be incremental. Generally, there is a lack of energy efficiency benchmark standards for industry at large and factories in various sectors [69], secrecy and antitrust legislation being important impeding factors. There exist corporate benchmarks in some companies that operate multiple plants or sites. Several consultants carry out benchmarking studies in various industries, e.g., Solomon Associates for steam crackers, Phillip Townsend Associates for polymerization plants, Plant Services International for ammonia and urea plants, and PDC (Process Design Center) for more than 50 petrochemical processing plants [70], to cite a few examples. These benchmarks present generalized and anonymized data with which the energy efficiency and the competitiveness of one's own plant can be compared to the industry average.

## Energy Efficiency World Records

Here is a brain-teaser: A world record in energy efficiency of a car was set in 2005 as 5,134 km/l of gasoline equivalent, operating on a hydrogen-powered PEMFC (polymer electrolyte membrane fuel cell) [71] during the Shell Eco Marathon. On the website of this annual competition [72], additional records on energy efficiency are highlighted, e.g., an equivalent of 3,771 km with 1 l of fuel with a combustion-engine powered car in 2009 (5 years earlier, the record was 3,410 km). These figures, equally impressive and irrelevant for current practical road transportation, show that there is plenty of potential left to increase energy efficiency, even beyond current imagination.

## Some Not-So-Energy-Efficient Inventions and Practices

Here are some examples of low-energy-efficiency appliances and habits, most of which might soon astonish people that they even existed in our times:

- Incandescent light bulbs
- Huge private cars such as SUV with single occupancy

- Standby function on electrical appliances in households
- Patio heaters to warm open areas outside the house
- Melting snow in cities such as New York City to dispose of it
- Flaring of hydrocarbons of low value in petroleum refineries
- Room temperature regulation by opening and closing a window, while keeping the heater switched on
- Water ring pumps to produce an industrial vacuum

In a typical household, appliances on standby use up 10% of the total amount of electricity consumed. This is equivalent to 400–500 kWh annually, virtually wasted with no energy service rendered.

## Barriers to Energy Efficiency

There is no doubt about the fact that energy efficiency offers cost-effective energy savings. However, the full potential has barely been tapped into. There are several barriers, associated with financial limitations, uncertainty, or others. They can also be classified as structural, behavioral and related to availability [9].

Though businesses and households are responsible for implementing most energy efficiency investments, it is their governments to provide the right bordering conditions to catalyze investments in energy efficiency by offering tax incentives, education, or other facilitation. One reason why the potential for energy efficiency has not yet been realized to its full extent is the fact that high upfront investments are often necessary, whereas the savings accrue incrementally over the subsequent years [9]. Also, the energy efficiency improvement potentials are highly fragmented [9]. Apart from low awareness, the difficulty to measure energy efficiency improvements in several areas contributes to slow progress. Barriers to energy efficiency are discussed in [9], alongside the following potential actions to break down these barriers:

- Information and education
- Incentives and financing
- Codes and standards

Experience shows that consumers are particularly hostile toward funding of energy efficiency measures, compared to businesses, even if the economics are reasonable. They apply hyperbolic discounting, meaning that immediate value is regarded significantly higher than future one.

Barriers toward energy efficiency improvements in industrial settings are reviewed in [32]. Another interesting question is the durability of energy efficiency measures, which was studied in [73], the results of which are given in ➲ *Table 24.4*. The percentages in ➲ *Table 24.4* reflect the portion of the first year energy savings that remain throughout the full lifetime of the studied energy efficiency measures. A distinction was made between measures focused on saving electrical energy and measures to save fuel. It can be seen that already after a few years, considerable losses from the initial gains are encountered, which

**Table 24.4**

**Estimated persistence of energy efficiency measures [73]**

| Years following implementation (installation) | Remaining energy efficiency impact | |
|---|---|---|
| | Electricity-related measures | Fuel-related measures |
| 1 | 99.69% | 100% |
| 2 | 95.97% | 99.46% |
| 3 | 89.59% | 98.51% |
| 4 | 85.14% | 97.84% |
| 5 | 84.02% | 97.11% |
| 6 | 78.32% | 89.75% |
| 7 | 78.22% | 89.75% |
| 8 | 78.22% | 89.75% |
| 9 | 74.58% | 89.70% |
| 10 | 66.73% | 87.45% |

can be explained by various factors depending on the efficiency measure. "Hard-wired" energy efficiency initiatives will generally be lasting longer than those based on behavioral changes (see also below).

An example how energy efficiency can stagnate if the economic and organizational conditions are not in favor of it, such as prevailing low electricity prices, is shown for the Swedish building industry in [74] and [75]. Aspects of financing energy efficiency, another prominent barrier, are outlined in [76–79]. Barriers to energy efficiency in general are reviewed in [80].

## Levels of Energy Efficiency: From Process to Behavior

Energy efficiency can be achieved by various means. A product can be manufactured in a way that energy is used efficiently, either during its production or during its use. A process can be energy efficient by itself, or it can produce energy-efficient outcomes. The same applies for services. Here are some examples of more and less efficient products and processes:

- Office lighting by compact fluorescent lights vs. traditional incandescent light bulbs
- Modern compact passenger car vs. older, midsized model
- Cement production by the dry process vs. the wet process
- Air separation by pressure swing adsorption vs. air separation by cryogenic air cooling and fractionated distillation
- Steel manufacture from scrap metal vs. ore

It is desirable to have efficient equipment and processes in place. However, these can be operated in very inefficient ways. The magnitude of loss in energy efficiency by "bad"

operation can be as large as the difference between competing processes and equipment items [41]. Some examples of these "bad" operation aspects are

- Excessive speeding with a car, which strongly increases fuel consumption/km
- Neglected maintenance on insulation of window frames in a private home
- Keeping office lights on overnight when they are not needed
- Operating plant utilities at full capacity during idle production times
- Not repairing leakages on compressed air pipelines

In contrast to the installation of new, more energy-efficient equipment, or the design of a more energy-efficient process, operation thereof requires constant attention (compare also the table above, showing the stunning erosion of energy efficiency gains over a few years' time). By continuously working on a mindset toward energy efficiency, for instance, by having employees turn off idle equipment and by fostering continuous improvement, also small, individual savings can add up. In [41], some aspects of why operators in control rooms do not always give utmost importance to energy efficiency are listed:

- Lack of urgency, little incentives to value long-term performance vs. the short term
- Preference of steady state operation vs. short-term optimization efforts
- Comfort, trading economy against less effort
- Individual work history and anecdotes making risk perception highly personal
- Different levels of skills and knowledge
- Instinct to preserve assets rather than maximize their utilization
- Little effect of administrative control measures alone
- Focus drift due to distraction

The most economic mode of operation of a plant in the process industries, for instance, is not always the most convenient one [41]. This will lead operators to at least partly refrain from energy efficiency optimization.

Such "human factors" can be improved by considering the *usability* of processes and equipment. Whereas the usefulness of a man-made tool or installation is related to user satisfaction, the term us(e)ability denotes the ease with which it can be deployed. In general, usability can be defined as a measure of the ease with which a system can be learned or used, its safety, effectiveness and efficiency, and attitude of its users toward it [81]. In [82] and [83], two examples of the successful application of usability and *usability engineering* in process control systems and industrial plants are given.

## Energy Efficiency Investments

As energy-efficient technologies often have higher initial investment costs than older, less-advanced ones, economic aspects will determine the extent to which energy efficiency is considered for new investments and for retrofits alike. The TCO (total cost of ownership) approach will clearly recommend energy efficient, but typically more expensive installations, in many cases. Investing in "the right technology," if it is not supported by a sound

business case of yearly energy-bill savings, will be easier during the construction of a new building or factory than when one wants to apply for funds, corporate and federal alike, later on. In industry, one can distinguish between

- Pure capacity investments
- Pure energy efficiency investments
- Hybrid capacity and energy efficiency investments

Common appraisal methods for investment projects in industry are

- Payback period
- Net present value (NPV)
- Internal rate of return (IRR): Discount rate where NPV = 0
- Strategic fit

Approval can be based on an evaluation of several of these parameters, by a ranking or by fulfilling a certain cutoff criterion. To test the validity of the profitability calculation of such a project, a sensitivity analysis can be carried out by varying the most important parameters. Monte Carlo simulation enhances the quality of such simulations [84]. Real options [85] can also be used. While debottlenecking investments, which increase production capacities, usually have short payback periods and high IRRs, often exceeding 50%, energy efficiency investments sometimes cannot make it over the 10% hurdle. If the funds for investment projects are limited, which is said to happen more often than none, naturally those with higher IRR will be preferred. Energy efficiency investments can be carried out at a lower IRR than a corporation's normal hurdle rate (IRR) because the associated risk is generally lower than for a capacity investment (energy savings can be predicted more reliably).

Often, when "selling" an energy efficiency project in a corporation, one had better avoid the term "energy," and describe potential projects as "efficiency" or "productivity" improvement projects when presenting them to decision makers.

Energy has a different importance for various sectors. Those industries which are energy-intensive will suffer more from high and volatile energy prices than the ones incurring only a small percentage of their costs from energy bills. It is estimated that out of the total global economic activity (€91,000 billion in 2008), 40% comes from companies where energy plays a strategic role [36]. The sectors concerned are transportation, building and construction, energy-intensive industries, engineering, IT (information technology), and the energy industry. For companies in these sectors, energy can have a direct or indirect effect, i.e., on their own production costs or on the acceptance of their products. On the other side, there are industries such as education, retail, insurance, and health care, which do not depend as much on energy competitiveness.

## Introducing Energy Efficiency Programs

It is estimated that most organizations have a potential for 10–20% energy efficiency improvement, which will materialize in the bottom line. In order to improve energy

efficiency in a company or another larger institution, an *energy survey* or an *energy audit* can be a first step to map out the savings potential. More information on such energy audits can be found in [86] and [87]. They consist of data collection ("hard facts" such as electricity consumption and interviews on common practices) and internal and external benchmarking. There is currently a lack of qualified energy auditing staff [69]. Checklists can help to uncover inefficiencies in processes and equipment. Using off-peak hour-electricity is an option to shrink the electricity bill. How to manage energy efficiency in a corporation is described in [88]. To which extent agreements foster energy efficiency is analyzed in [89].

## Combustion

Combustion plays a critical role in energy efficiency considerations, as approximately 80% of global primary energy is produced by combustion processes. Combustion processes have the single largest human influence on climate with 80% of anthropogenic greenhouse gas emissions [90]. Fuels can be fossil or renewable (biomass). They are gaseous, liquid, and solid.

Combustion is used in power plants for electricity and heat production, transportation, and other areas (see sections below for details). *Figure 24.7* shows the global trend in $CO_2$ emissions over the last 140 years [90]. As it can be inferred from the above *Fig. 24.7*, the increase in anthropogenic, combustion-derived $CO_2$ emissions has almost been an exponential one. For the impact on climate change, not only the efficiency of a combustion process itself, but also emissions generated during fuel production and transportation have to be considered. For instance, for every kilogram of mined coal, 1.2–16.5 g of the greenhouse gas methane are emitted [22]. Combustion can be

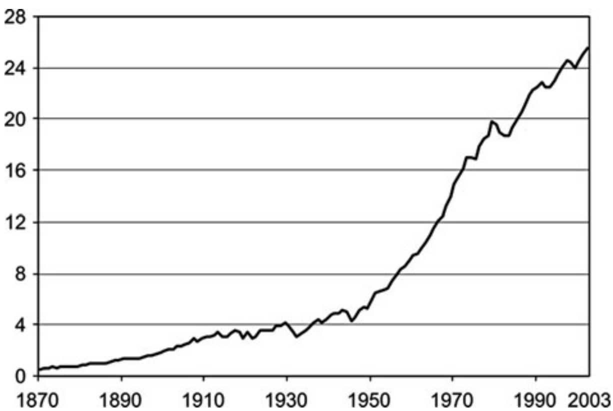



**Fig. 24.7**

**Trend in $CO_2$ emissions from fossil fuel combustion. Units: Gigatons of $CO_2$ (Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, TN, USA. Reprinted with permission from Elsevier from [90])**

carried out in furnaces (see power plants below) and boilers, internal and external combustion engines, and in gas turbines [91–93].

*Pyrolysis and gasification* are special cases of combustion. These processes can be used to obtain gaseous or liquid fuels from biomass or coal in conjunction with a Fischer–Tropsch [18, 94] or other synthesis process. Due to the removal of moisture and ash, and the effect of deoxygenation, liquid hydrocarbons derived from biomass have a threefold energy density and are hence more advantageous for transportation and storage [16]. See also the chapter on gasification in this handbook.

Heat recovery from flue gases is a particularly energy-efficient measure. For steam systems, for instance, 1% of fuel can be saved for every 25°C reduction in exhaust gas temperature [95]. In [90], recent trends on $CO_2$ emissions from fuel combustion are reviewed. For combustion in general, see [96].

## Power Plants and Electricity Production

Twelve percent of man's total energy is made up by electricity, a fraction that is expected to rise to 34% until 2025 [97]. Energy efficiency in electricity production can be defined as the energy content of the produced electricity divided by the primary energy input, with reference to the lower heating value [52]. The lower heating value (LHV, or net calorific value) assumes that the water formed in combustion remains as vapor. In *cogeneration*, the overall efficiency can be increased because the (by-product and formerly waste-) heat is used. Cogeneration is also dubbed *CHP* (combined heat and power).

Power production is carried out by (large) public power and CHP plants and by so-called *autoproducers*. These are users such as chemical factories which produce their own power and heat. In the EU, autoproducers account for 8% of the total power generation [52]. Electricity production plants have an efficiency of around 30–40%, whereas combined heat and power (CHP, cogeneration) yields up to 90% [22]. For the installed base of CHP, see [98].

In the EU, the energy efficiencies for coal-fired power production range from 28% (Slovak Republic) to 43% (Denmark). On a global scale, the spread for oil-fired power plants is an efficiency of 23% for the Czech Republic and 46% for Japan [52].

The efficiency of a given power plant is dependent on its age. The younger a plant, the higher its energy efficiency was (intuitively) found to be [52]. These findings are in line with another study [65], which revealed that the least energy-efficient plants are not always located in developing countries. Apart from the age of a plant, its fuel mix, size, and load account for the big differences in efficiencies mentioned above (see also section below on "Crosscutting Technologies").

State-of-the-art power plants based on coal and gas have energy efficiencies of 46% and 60%, respectively [52]. It is estimated that the replacement of inefficient coal-fired power plants by more efficient coal- or gas-fired ones, particularly in China and in the USA, can reduce global $CO_2$ emissions by 5% [5]. In Canada, in 1988, according to the Canadian Industry Program for Energy Conservation (CIPEC), the average $CO_2$

emissions in electricity production were 0.22 t/MWh, with a spread of 0.01 in Quebec to 0.91 in Alberta [22].

*Demand side management (DMS)* can help to level peak electricity demand [101]. *Energy* is increasingly being produced *from waste*. Methane can be extracted from landfills for power production in gas engines. Waste incineration uses the energy content of waste and converts it to a low-volume, inert residue. While previously, the focus of waste incineration plants was on low-emission combustion to get rid of the waste, today the energy efficiency of these plants has become important, too. In [99], an incineration plant for medical waste is presented. It is equipped with a heat recovery system and can extract 660–800 kW of usable energy from 100 kg/h of medical waste with an energy efficiency between 47% and 62%. New and innovative pyrolysis and gasification technologies for energy-efficient waste incineration are presented in [102]. In [103], waste incineration is compared to landfilling, and in [105], a life cycle assessment (LCA) [104] of waste management strategies is performed.

## Energy Transmission and Distribution

Today, electricity production is centralized, with large power plants being coupled to a complex distribution network. Energy transmission and distribution cannot be performed in a totally loss-free way (leaving apart superconductivity, where electrical resistance is exactly zero). In Europe, they typically amount to 4–10% and hence reduce the overall efficiency of power supply by several percent points [52]. Transporting the fuel to end users is more cost-effective, yet also consumes substantial amounts of energy (see sections on pipelines, land, and sea transportation below). Natural gas, for instance, is being pumped across long distances because placing a gas power station next to the gas field and transmitting the electricity and heat would result in a considerably lower overall efficiency than compressing and moving the gas through pipelines.

## Energy Storage

The need for more and cleaner energy leads to an increase in distributed generation (DG) and renewable energy sources (RES) [106]. Since such sources like wind power are not as reliable and as simple to adjust to demand fluctuations as conventional power plants, they could be coupled with energy storage systems.

Power demand by (end)users fluctuates strongly. Typically, the lowest consumption during a 24 h-period is nearly half the peak demand, compare ➲ *Fig. 24.8*. Today, with a mainly centralized electricity production scheme, there is only a small storage capacity available, amounting to approximately 90 GW or 2.6% of the total production of 3,400 GW [97]. With DG and RES on the increase, it is expected that energy storage, more specifically electrical energy storage, will gain significance on a local (small) and regional (large) level.

Energy can be stored in various ways, for instance as

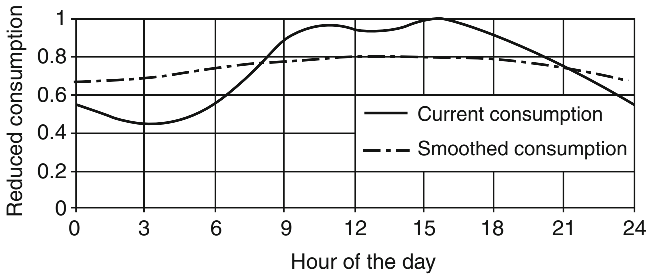



**Fig. 24.8**
**Average daily power consumption in France, reprinted with permission from Elsevier from [97]. Peak demand happens in the morning and afternoon, with the lowest demand being met in the early morning hours**

Potential energy: Pumped hydro storage (PHS, i.e., pumping water up into a reservoir so that it can later drive a turbine), or compressed air energy storage systems (CAES, i.e., compressing gas in a cylinder)
Kinetic energy: Accelerating a flywheel
Chemical energy: Batteries [107], fuel cells ($H_2$)
Thermal energy: Use of sensible or latent heat [97], e.g., of NaOH

Lead batteries are well known for the storage of energy; however, they are heavy and inapt for high cycling rates. Reference [107] discusses the energy efficiency of batteries.

In [97] and [106], an overview on current and future energy storage technologies is given. They differ in their maturity, target use (e.g., portable or fixed, long- or short-term storage), specific power (power density) (W/kg) and specific energy (energy density) (Wh/kg), the lifetime (number of cycles), the self-discharge rate, and the costs per installed kilowatt-hour. Hydrogen storage options are reviewed in [108]. In [97], the energy efficiencies of various energy storage technologies are compared.

## Life Cycle Assessment (LCA)

*Life cycle assessment (LCA)* [104], also called *life cycle analysis*, is a holistic view on a product or service. As the name implies, all steps from its raw material production, manufacturing, transportation, distribution, use, and disposal are considered to determine the overall effect that a given product has on the environment. LCA is rooted in the ISO14001 environmental management system standard, more specifically in ISO 14040, 14041, 14042, and 14043 [109].

Variants of life cycle analysis are

- Cradle-to-grave analysis (full life span)
- Cradle-to-cradle analysis (including recycling)
- Cradle-to-gate analysis (partial process)

- Gate-to-gate analysis (one step)
- Well-to-wheel analysis (used in the automotive industry, see below)
- Wire-to-water efficiency (used for pumps, see later)

Eco-balance is a synonymous expression for LCA. An illustrative example for the value of LCA is the use of plastics materials for insulation purposes. Within 4 months of use, the energy savings can equal the energy needed for production, with a service life of up to over 50 years [70].

In transportation, LCA is typically done as well-to-wheel (WtW) analysis, which is an overall fuel efficiency calculation (there are also the standard LCA studies for cars, ranging from production to use and disposal). *WtW efficiency*, detailed in [94, 110–112], is a similar concept as *life cycle energy efficiency* [27]. Both concepts can be understood as overall efficiencies of a process chain, calculated as the product of the individual efficiencies.

WtW efficiencies allow meaningful comparisons between different technologies, for instance, internal combustion engines (ICEs) vs. fuel cell (FC) vehicle technologies. They provide for a fair comparison. *Figure 24.9*, taken with permission from [113], shows the efficiency chain for different automotive propulsion systems under hot-start conditions.

In *Fig. 24.9*, the WtW efficiency is calculated as the product of conversion efficiency $\eta_c$, distribution efficiency $\eta_t$, and propulsion system efficiency $\eta_p$ as shown in Eq. 24.6 below:

$$\eta = \eta_c \eta_t \eta_p \tag{24.6}$$

The conversion efficiency $\eta_c$ for gasoline and diesel production in a refinery is quoted as 88% in [114] and as 63% for their production from methanol according to the Lurgi process (20 years ago), and the distribution efficiency $\eta_t$ as 97–98% in [70].

In *Fig. 24.9* above, it can be seen that the CNG-SOFC (compressed natural gas-solid oxide fuel cell) combination achieved the best overall efficiency of around 35%, with the best internal combustion engine performance being 29% for diesel from crude oil [70].

The *eco-balance* of biodiesel, for instance, has to consider the consumption of fossil fuels and materials for its production, e.g., the use of lubrication oil. Another important term is that of the "energy path." The production process will strongly impact energy consumption. Methanol, for instance, can be produced via a path starting from sugar cane, or from natural gas, which will yield different eco-balances.

An interesting website on LCA is run by the US Environmental Protection Agency EPA [115].

A related concept to LCA is the *embodied energy* [116]. It is often used for buildings (see later). Also in other industries, significant amounts of energy are "stored" in the final product. In the case of the petrochemical and chemical industries, which consume 30% of global industrial energy, more than half of the energy is locked up in the final products [70] and can be recaptured at the end of their lifetime.

The total life cycle of a product can not only be assessed with regard to energy use and environmental aspects, but also from an economic point of view – in terms of costs. In this case, one speaks about *life cycle costs* (*LCC*) or total cost of ownership (TCO).

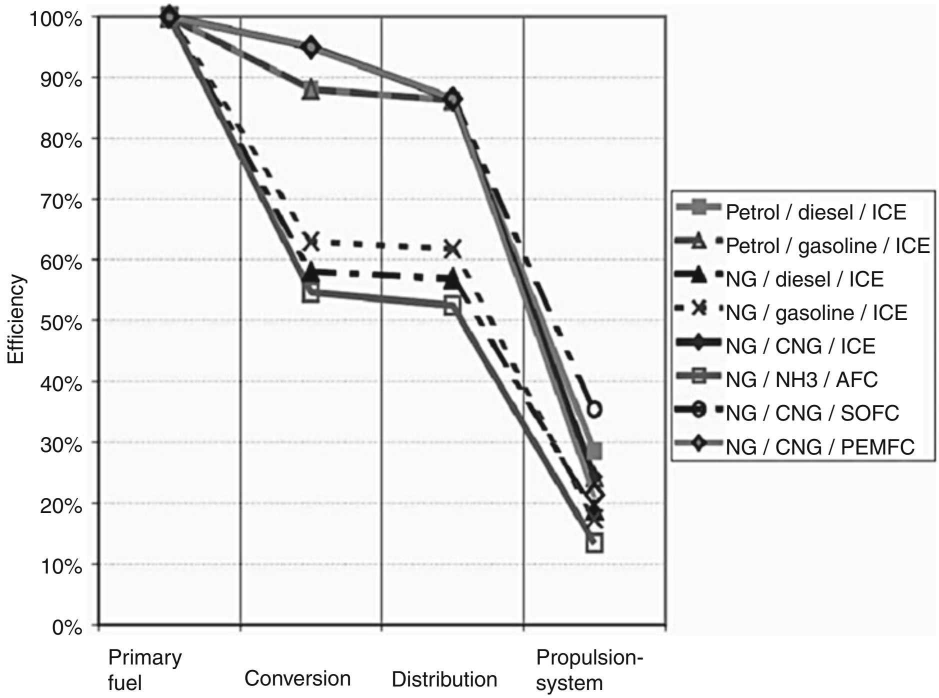



**Fig. 24.9**

**Well-to-wheel efficiencies under hot-starting conditions. *ICE* internal combustion engine, *NG* natural gas, *CNG* compressed natural gas, *AFC* alkaline fuel cell, *SOFC* solid oxide fuel cell, *PEMFC* polymer electrolyte membrane fuel cell (Reprinted with permission from the Society of Automotive Engineers (SAE) from [113])**

*Recycling* is an important aspect of life cycle assessment. The primary energy demand for "new" materials is often considerably higher than that needed to recycle them from waste. For instance, if aluminum cans are recycled, the energy consumption will only be 5% of the energy needed to make them from virgin bauxite ore. Scrap metal, glass, paper and plastics should be recycled to make best use of their "energy content" as primary production tends to consume more energy than secondary one. In the case of plastics, "thermal recycling" is an advantageous, final use if other uses are not feasible. The 3R (*reduction, reuse, recycling*) are approaches to limit the quantity of primary raw material demand, hence contributing to sustainability.

## Total Cost of Ownership (TCO)

The total cost of ownership (TCO) concept acknowledges the fact that the use of any equipment has two types of costs associated with it:

- Initial investment costs
- Running costs over the entire useful life time (energy, maintenance, disposal, etc.)

For industrial pumps, for instance, which are typically in service for 15–20 years, the initial investment cost is often less than 5% of total incurred costs [117]. For a majority of industrial assets and facilities, the lifetime energy will dominate the life cycle costs, which is also the case for many equipment items in private homes. More information on TCO can be found in [118, 119], and [80], with the latter two providing ample coverage of economic evaluation of energy efficiency.

## Energy Efficiency in Various Sectors

In the following sections, energy efficiency in various areas is discussed. As it was shown in ➲ *Fig. 24.1* and ➲ *Table 24.1*, major consumers of energy are end users, power plants, transportation, industry, buildings, and others, each of them showing potential for cost-effective energy efficiency improvements.

### Agriculture and Food

Agricultural activities make a strong contribution to anthropogenic climate change. Greenhouse-gas emissions from this sector account for 22% of global total emissions, which is similar to the contribution level of industry and greater than that of transportation. Livestock production (including transport of livestock and its feeding) accounts for nearly 80% of the sector's emissions [120]. The two strong greenhouse gases (GHG), methane and nitrous oxide (which are closely linked with livestock production), contribute much more to this sector's warming effect than does carbon dioxide [120]. Emission factors of $CO_2$ and $CH_4$ for livestock are estimated at 36–3,960 and 0.01–120 kg per head and year, respectively [22]. Agricultural operations not only put strain on global climate by $CH_4$ emissions from cattle, but also by energy consumption, which is concentrated in the areas of irrigation, process heat applications, and refrigeration. Irrigation pumps, refrigerated warehouses, greenhouses, and postharvest processing offer various potentials for energy efficiency improvements. A nice example is provided by some Dutch greenhouses, which are heated by gas engines, the $CO_2$ from which is fed into the greenhouses to fertilize the plants and to boost their growth [121]. In [122], different heating methods for greenhouses are compared. In [123], the energy efficiency of the Dutch food industry is reviewed, and in [301], that of the European dairy industry. Additional case studies of recent improvements in energy efficiency in the agricultural industry are discussed in [124].

The energy use for the production of various agrichemicals, such as herbicides, growth regulators, and fungicides, ranges from 120 to 550 MJ/kg of active ingredient [125], taking production, packaging, and transportation into account [125]. The application rate of these chemicals further determines the total energy consumption per kg of agricultural product.

*Food miles* are a very simplistic concept relating to the distance food travels as a measure of its impact on the environment [125]. While a lower number of "food

miles" will generally render a product more energy efficient because transportation ways are shorter, a food commodity that is produced with high energy efficiency, e.g., by little use of fertilizers, and that has a long mileage to the consumer, can still have a lower environmental impact that foodstuff manufactured close to the end customer in an otherwise inefficient way. This simple example shows that energy efficiency aspects are closely interwoven and often difficult to compare, not only in the agricultural industry. Globalization affects the food industry as much as it does high-tech goods: The fraction of vegetable and fruit imports from New Zealand to the EU is 12% and 7%, respectively (figures of the year 2002) [125]. In [126], energy efficiency in the food industry is treated in detail.

## Transportation and Logistics

Our world has become global so that people and goods are being transported between countries and continents on a large scale. The IEA predicts significant improvements in energy efficiency in transportation; however, these will be more than offset by increased travel [5] and further globalization.

Fuel efficiency in transportation ranges from a few megajoules per kilometer and passenger for a bicycle to several hundred megajoules for a helicopter. Approximately one third of the energy consumption in transportation is used for freight movement [127], which accounts for 8% of total anthropogenic $CO_2$ emissions. Most of these emissions stem from trucks (heavy goods vehicles, HGV), which account for most freight activities in most countries, e.g., 68% of all ton kilometers in the UK [127]. Ample road networks make cargo distribution by HGV convenient and efficient in terms of time and costs.

### Road Transporation and Internal Combustion Engines

Although rail and ship transportation are more efficient and environmentally benign than road transportation, trucking is still heavily used for reasons of flexibility, costs, and timeliness, not only in weakly developed areas, to move goods and people.

Most vehicles on the road today are powered by internal combustion engines (ICE). Engine and propulsion system selection for cars is based on various criteria such as driving performance, range, and safety. ICE burn gasoline and diesel, the latter being used for trucks and, in some countries, private cars, with natural gas-, ethanol- and hydrogen-propelled cars constituting a minor fraction next to those with alternative systems such as electrical batteries or air buffer tanks. Internal combustion engines have become more efficient over the last decades. The largest losses in gasoline engines are encountered by throttling the engine [113].

Reference [128] estimates that over the next decade, an efficiency improvement of another 6–15% is feasible. Various optimizations such as direct fuel injection, variable valve timing, supercharging, downsizing, exhaust gas recirculation, onboard fuel reforming, and power train improvements, e.g., on the gearbox, are being tested and

implemented [113]. The reuse of losses also offers significant potentials, for instance, recuperative braking or the extraction of heat from exhaust gases.

Stationary engines, such as large gas engines for power backup or landfill gas use, can be operated in steady mode at optimum efficiency. Combustion engines in mobile machines have to perform well over a wide range of load, which yields poorer overall efficiency.

A novel, promising combustion technology for engines is HCCI (homogeneous charge compression ignition) [129]. HCCI is a hybrid between an auto-ignited Diesel engine and a spark-ignited Otto engine in that it deploys autoignition of a homogeneous fuel–air mixture. Alternative ignition systems [130] such as laser ignition are also expected to improve fuel economy. For a discussion on internal combustion engines for future cars, see [131].

## Passenger Cars

It is estimated that by 2030, 60% of all new cars sold will be *hybrids*, plug-in hybrids and *electric vehicles*, as opposed to 1% today [5]. Hybrid cars combine an electric engine and an internal combustion engine. Dual fuel concepts (natural gas and diesel, for instance), are also feasible. The $CO_2$ intensity of the passenger car fleet in 2030 is estimated to be 90 g of $CO_2$/km, compared to 205 g/km in 2007, as a worldwide average. In OECD countries, it should reach 80 g, in the EU 70 g, and in India and China 110 and 90 g, respectively, in 2030, the latter ones down from 225 and 235 g, respectively, in 2007 [5]. On the other hand, a large increase in the global number of cars is anticipated, particularly in developing nations such as China and India.

Hybrids use regenerative breaking to recapture energy that would otherwise dissipate. The effect on fuel economy of such cars is particularly pronounced in stop-and-go city traffic. Fuel economy of private cars is governed by the following aspects:

- Technology advances of the car, e.g., better engine
- Driving habits (use of air condition, cruising speed, payload in the car, etc.)
- Maintenance (no clogged air filters, correct tire pressure, etc.)
- Weight (lightweight construction materials can save fuel over the entire lifetime)

There is plenty of information available for consumers who want to pick an energy-efficient car, e.g., one website run by the US EPA [132]. In California, *partial-zero emission vehicles* (*PZEVs*) were introduced to satisfy part of the state's *Zero Emission Vehicle* (ZEV) Program [133]. In [134], options for carbon-neutral passenger transport are reviewed.

Reference [135] compares fuel cell and battery electric vehicles. The primary energy efficiencies of alternative powertrains in vehicles are discussed in [136]. In [113], the energy efficiency of internal combustion engines and fuel cells for automotive use with different fuels is assessed. It is concluded there that fuel cells have an advantage during hot-start conditions but suffer from efficiency losses during cold starts [113].

Although the energy efficiency of a fuel cell-powered car is not the best, the environmental performance of a vehicle burning hydrogen from solar generation in a low-noise,

virtually emission-free fuel cell are outstanding. It is expected that the fraction of fuel cell cars will increase over the next decade, with an accompanying growth of the necessary infrastructure.

## Ships

Ninety percent of the world's trade is carried by the international shipping industry, supported by 50,000 merchant ships [137]. Over the last four decades total seaborne trade is estimated to have quadrupled, from just over 8,000 billion ton-miles in 1968 to over 32,000 billion ton-miles in 2008 [137]. Seaborne shipping is one of the most energy-efficient means of transportation, especially for large, bulky goods.

Here is a comparison of energy efficiency of different transportation modes taken from a study by the Swedish network for Transport and the Environment (*Table 24.5*) [137].

It has to be noted that this table is slightly biased in favor of sea transportation, as the aircraft mentioned is an outdated one used on a short-haul flight. Ships can be driven by different technologies [138] with diesel engines being most common. The resistance of the ship's hull, the design, or the propeller and the tonnage are important factors for its energy efficiency as well. The impact of shipping on the atmosphere and on the climate is discussed in [139]. The auxiliary powering of ships by kite-like devices is discussed in [140] and [141]. Spinning vertical rotors installed on a ship to convert wind power into thrust based on the Magnus effect, so-called Flettner rotors, are another option to increase energy efficiency. Microbubbles as a means of reducing skin friction on ships are studied in [142]. Different propulsion systems for LNG carriers are discussed in [143]. LNG (liquefied natural gas) is expected to gain an increasing importance.

## Rail Transportation

Intuitively, rail transportation of people and cargo is amongst the most environmentally friendly modes of movement. Technological progress has increased energy efficiency in

**Table 24.5**

**Energy consumption in different transportation modes (dwt is the deadweight tonnage (also known as deadweight, DW or dwt), a measure of how much weight a ship can safely carry. It is the sum of the weights of cargo, fuel, ballast water, crew, etc.) [137]**

| Mode | Air | Road | Sea | Sea |
|---|---|---|---|---|
| Comment | B727-200 (1,200 km flight) | Medium-sized truck | Cargo ship, 2,000–8,000 dwt | Cargo ship, >8,000 dwt |
| Energy consumption | 4.07 kWh/t km | 0.49 kWh/t km | 0.08 kWh/t km | 0.06 kWh/t km |

rail transportation, too. According to [144], aerodynamic drag per seat at 150 km/h was cut by half over 30 years. Train speed determines energy efficiency. The energy consumption for a high-speed train from London to Edinburgh increases from 30 to almost 60 kWh/seat as the speed goes up from 225 to 350 km/h [145]. The American railway corporation Amtrak reported an energy use of 2,935 BTU per passenger-mile (1.9 MJ/passenger-km) in 2005 [146].

A critical factor in energy efficiency of trains is the occupancy. If a train is only 25% loaded, the fuel consumption per passenger and seat can be worse than with economic cars and modern aircraft as shown in [147].

## Air Transportation

Aviation has helped shape our current business dealings and lifestyles significantly. Virtually any point on the globe has got into easy reach within 24 h. Air transportation is used for cargo and people. It has contributed approximately 3.5% to global greenhouse gas emissions in 1990 with a projection of 15% or more in future [148]. The impact of aviation on climate change is not only driven by $CO_2$ emissions, but also by $H_2O$ emissions at high altitude [149]. Due to the long residence time of water vapor at aircraft cruising altitude, it can disproportionally contribute to global warming by reflecting and retaining infrared radiation (compare the effect of natural clouds). Biofuels for aviation [150] were already tested in a proof-of-concept study [151], provoking mixed feelings amongst critics. Winglets [152] and lightweight materials [153] are two commonly known concepts to increase fuel efficiency of aircraft, hence increasing energy efficiency. See also ➲ *Figs. 24.4* and ➲ *24.5* above.

## Pipeline Transportation

Pipelines [154], i.e., conduits of pipe, can be used to transport liquids, gases, and slurries. The Romans built aqueducts for water transportation some 2,000 years ago. An early industrial pipeline was installed in Austria in 1595 to transport brine from Hallstatt to Ebensee for salt production [155]. Today, pipelines are commonly used to transport petroleum, natural gas, and other commodities over large distances. A comparison of natural gas transportation by LNG tankers and pipelines is made in [156]. LNG compression and regasification consume 7–13% of the original amount of natural gas, as well as roughly 0.15% per day of marine transport, which adds about another 1% to overall energy losses. Pipeline transportation of natural gas results in energy losses of approximately 1% per 1,000 km. Therefore, an intercontinental 8,000 km pipeline would involve energy losses of roughly 10%, which is approximately half the amount of transportation by LNG tankers over the same distance [157]. The transportation of liquids in pipelines vs. onboard of trucks is compared in [157] and [158]. The conveying of coal as a slurry in pipelines is assessed in [159]. In industrial plants, pneumatic conveying (dense phase or dilute phase conveying of a solid in air) and hydraulic conveying (solids in liquid carrier

media) are used to transport materials between various processing sections. Variable speed drives (VSD) for pneumatic conveying blowers are a means of enhancing energy efficiency vs. blowing off excess air at low conveying capacities for the transportation of solids in the gas phase. Reference [160] reviews the transportation of biomass in pipelines. It is concluded that long distances and high throughput rates make such systems economic, as is generally the case with pipeline transportation.

## Industry

Industry accounts for a high fraction of the global energy consumption, see *Table 24.1* above. The energy intensity varies strongly from 52.3 end-use BTUs per USD of value added in cement production to 0.4 end-use BTUs per USD in computer assembly [9]. Ten end-use BTUs per USD can be set as limit for energy-intensive industries as done in [9].

There is a huge potential for energy savings in industry, yet the biggest opportunities for optimization are not easily known to the people involved [69]. Approximately two third of the energy savings potential can be found in specific process steps of energy-intensive industries, whereas one third resides in various areas of non-energy-intensive ones. Savings can be realized by more efficient processes or by more efficient equipment.

### Crosscutting Technologies

Equipment which is used in different sectors of industry, such as lighting, motors, boilers, and pumps, is subsumed as crosscutting technologies. For these, best practices (see, e.g., [161]) and general recommendations can be formulated that are valid for several branches and sectors of industry. Generally, there exist untapped-into savings potentials in

- Waste heat recovery
- Steam systems
- Motor systems
- Pumps [117]
- Lighting
- Buildings
- Utilities

For quantifying energy efficiency potentials, there are various methods [24]. Here are some aspects of energy efficiency that are relevant for many industries:

*Process design*: The largest contribution to energy efficiency is made during the design of a process. If a product, for instance, has to be heated up and cooled down several times, chances are high that the process is not energy efficient. Also, an implemented production process is difficult to change.

*Overcapacity*: Design capacity should meet the needs for a process in terms of vessel size, engine power, etc. Overdesign always costs money – not only in the investment phase, but most likely also later on, when energy consumption is higher than necessary.

Overcapacities of process equipment should normally not exceed 10% of the overall design capacity.

*Debottlenecking*: If a plant can be deblottlenecked, i.e., the output can be increased by making some small modifications, one typically has a highly profitable project. Also from an energy efficiency perspective, debottleneckings frequently lower the specific energy consumption of a product, thus making it more energy efficient.

*Measuring, monitoring*: In order to be able to track energy efficiency measures, it is necessary to measure accurately and regularly actual consumption values of electricity and other utilities such as compressed air or cooling water. Only by monitoring them actively will deviations be spotted.

*Automatic controls*: Automatic process control is generally faster and more accurate than a manual one, and also less prone to errors. Therefore, a production process can be carried out in the most energy-efficient way if it is automatically controlled. Automation will be more economic for large processing plants where the investment costs can be diluted over the volume.

*Compressed air*: Leaks of air from pipes can easily lead to 20–50% efficiency loss of a compressed air system. Preventive maintenance and the timely repair of leaks will help to minimize running costs. A pressure reduction of the entire system can often be considered, as instrument air (plant air) typically only needs to have ∼6 bar pressure, which is less than the design pressure of many compressor systems. If the operating pressure is reduced by just 1 bar, energy savings of over 5% can result.

*Maintenance*: If industrial assets are not properly being taken care of, their energy consumption tends to increase. Advanced maintenance techniques such as risk-based maintenance, preventive maintenance, thermography, and others will help to keep energy efficiency up. Cutting costs on maintenance can bring short-term gains at the expense of increased risk and deferred costs. A typical yearly maintenance budget for industrial plants would be 2% of the investment value, depending of course on the process.

*Cogeneration*: Production sites that produce their own electricity should seriously consider combined heat and power (CHP). If there is no need for heat in the installation itself, there might be an opportunity to sell the heat, e.g., for district heating purposes. Cogeneration will use the heat which would otherwise be wasted, thereby increasing the energy efficiency.

*Motors and drives*: It is estimated that two third of all electricity consumption in industry is used to drive various motors [161], so there is a huge optimization potential. The "motor challenge" is a recent program to improve motor efficiency [162]. Typical energy efficiencies of motors are 80–90%, with advanced models reaching 97% [22].

*Variable speed drives*: An engine's energy consumption can be matched to the load by using a variable speed drive (VSD). VSDs can be realized with a frequency converter coupled to an engine. Up to 50% of energy can be saved. Today, only an estimated 10% of all engines in industry are equipped with VSD. A large number of motors are still controlled by throttling valves in pump systems or vanes in fan applications. By throttling, a part of the produced output immediately goes to waste. Speed control with intermediate transmission such as belt drives, gearboxes, and hydraulic couplings adds to the

inefficiency of the system, and requires the motor to run at full speed. Another drawback is that such systems typically require more maintenance. They can be noisy, too.

*Pumps*: It is estimated that pumps consume 25% of the electricity in US manufacturing facilities [95]. Industrial pumps have a lifetime of 20 years and longer. Pump efficiency is defined as the pump's fluid power divided by the input shaft power, and is influenced by hydraulic effects, mechanical losses, and internal leakages. Pump manufacturers have devised many ways to improve pump efficiencies. For example, the pump surface finish can be made smoother by polishing to reduce hydraulic losses. A "good" efficiency for a pump will vary depending on the type of the pump. A more useful efficiency term is the *wire-to-water efficiency*, which is the product of the pump and motor efficiency. An even better measure of efficiency for analysis purposes is the *system efficiency*, which is defined as the combined efficiency of the pump, motor, and distribution system. See also [117] and *life cycle assessment (LCA)* above.

*Fans*: Fans move air as pumps move liquids. They can often be optimized for energy efficiency, e.g., by adding a VSD (see above).

*Energy management system*: An energy management system (EMS) is the energy equivalent of an environmental management system. Generally, industrial sites or units that consume more than 1,000 toe/day should have a dedicated *energy manager*, who will "pay himself" by economizing on energy bills. A guideline for energy management is provided by [22].

*Several smaller units instead of one large one*: Instead of one large pump which is controlled with a bypass, several smaller pumps might be more energy efficient, matching power consumption to the process needs. The same consideration might work for air compressors, etc.

*Energy audit* and *energy survey*: These tools were mentioned already earlier in this chapter. They can be administered by internal or external staff. Generally speaking, it is vital for the success of an energy efficiency program in a corporation to have the support of a senior, recognized executive and to make the effort lasting by introducing energy performance indicators, which can be linked to employee's targets and performance management.

*Improvement of power factor* (*cos* $\phi$): Power companies will grant a discount on a corporation's electricity bill if the power factor is OK.

*Load shifting* (using off-peak electricity): If energy-intensive production processes can be concentrated in off-peak hours, the energy bill will be lower. This will also have positive effects on the environment, as peak electricity demand often needs to be produced in a not-so-efficient way.

*Load shedding*: By reducing peak electricity consumption, energy costs can also be reduced.

*Insulation*: Process insulation can be optimized for energy efficiency. A waterlogged insulation transfers heat 15–20 times faster than a dry one, and one filled with ice even 50 times faster [22]!

*Using waste heat*: *Heat losses* are a major sink for energy. Process heat in general can be upgraded using *absorption heat pumps (AHP)*. Heat losses in flue gases are a particularly large term: If flue gases exit the chimney too hot, significant amounts of heat are wasted

(up to 1% of fuel savings for 25°C colder flue gas temperature [95]), see also cogeneration. As for *heat exchangers*, cleaning and optimization can bring additional energy efficiency gains [163].

An overview on energy efficiency improvement potentials in industry is given in [164] and [165], the latter focusing on mechanical systems. Industrial energy efficiency in Asia, where a large part of global energy-intensive industry has settled, is treated in [166].

## Steam and Boilers

Steam engines are gone; however, still 37% of the fossil fuel burned in the US industry is used to produce steam [167]. Steam is the working fluid in steam turbines for electricity production. It is used in various industries to transfer and to store heat as it is a capacious reservoir for thermal energy because of the high heat of vaporization of water.

The chemical industry uses significant amounts of steam as process heat, one reason being that steam is generated as a by-product in some processes in integrated chemical production sites. Steam in general can be produced efficiently in cogeneration plants. In contrast to district heating networks to heat private homes, cogeneration plants in industry can be operated at full capacity all year round. Steam is produced in *boilers*. Energy efficiency measures for boilers include

- Improved process control
- Reduced excess air
- Improved insulation
- Maintenance
- Recovery of heat from flue gas
- Recovery of steam from blowdown
- Optimization of fuel mix

For steam distribution systems, the following measures are effective:

- Improved insulation
- Improved steam traps
- Steam trap monitoring
- Leak repairs
- Condensate return

In [167], information on steam systems in industry, their energy use and energy efficiency improvement potentials are outlined. Detailed information on boilers is given in [168].

## Energy-Intensive Industries

There are certain "heavy industries" that consume a large fraction of total energy output. In China, for instance, the top 1,000 energy-intensive enterprises consumed 30% of

China's total energy and 50% of the total industrial energy in 2007 [169]. Energy intensity is a specific quantity, expressed as kWh/kg of product or as kWh/monetary unit (value added, often in USD). Above an arbitrary threshold of ten end-use BTUs per USD, one can speak about energy-intensive industries [9]. This classification is valid for the production of

- Cement (calcination process, clinker production)
- Steel (coke consumption)
- Aluminum (primary metal production by electrolysis)
- Ores (mining operations)
- Pulp and paper (mechanical pulping)

These industries have a strong effect on global energy consumption because they are not only energy-intensive as such, but because they produce high amounts of materials per year. The global steel production, for instance, is in excess of one billion tons [170]. The IEA predicts big improvements in energy efficiency in industry, which are expected to be more than offset by higher output of steel and cement [5], especially in the developing world, to which countries like Brazil, Russia, India, China (BRIC), Mexico, and South Korea belong. The following *Table 24.6* shows the changes in energy consumption in energy-intensive industries in China, reproduced from [171].

Energy production in China is largely based on coal combustion, with efficiencies being approximately 10% lower than in Europe or the USA [171]. The $CO_2$ emissions from coal combustion are naturally higher than those from other fuels with a lower C/H ratio. Several technology options to reduce energy consumption and $CO_2$ emissions in energy-intensive industries are reported in [172], see also below.

## Iron and Steel

In the iron and steel industry, as the name implies, iron production and steel production are the main processes [173]. Iron can be produced along different routes. The classic path is the production of pig iron from ore and coke in the blast furnace, which is then further processed into steel in the basic oxygen furnace (BOF) or the open-hearth furnace (OHF), the first one being more energy efficient. Smelt reduction and direct reduction (DR) are

**Table 24.6**

**Energy efficiency in China for energy-intensive products [171] (Taken from the Annual Report on China's Energy Development (2006) therein)**

| Branch of energy-intensive industry in China | 1990 | 2000 | 2004 |
|---|---|---|---|
| Coal consumption in thermal power generation (gce/kWh) | 427 | 393 | 379 |
| Comparable energy consumption per ton of steel (kgce/t) | 997 | 784 | 705 |
| Overall energy consumption in cement production (kgce/t) | 201 | 181 | 157 |
| Overall energy consumption in ethylene production (kgce/t) | 1,580 | 1,212 | 1,004 |

*Gce* gram of coal equivalent, *kgce* kilogram of coal equivalent

**Table 24.7**

**Potential technologies to make energy-intensive production processes more efficient [172] (From IEA, DOE, AISI, Aluminum Association, Korean Energy Institute)**

| Technology option | Description | Time frame |
|---|---|---|
| Pulverized coal and plastic waste injection | Pulverized coal is already used by more than 50% of all US BOFs | ST-MT |
| New reactor designs | Uses coal and ore fines (COREX™, FINEX™) | MT |
| Paired straight hearth furnace | Substitutes coal for coke in blast furnaces, lower costs, uses two third energy | MT-LT |
| Molten oxide electrolysis | Produces iron and oxygen, no $CO_2$ | LT |
| Hydrogen flash melting | Uses hydrogen in shaft furnaces, no $CO_2$ | MT |
| Geological sequestration and steelmaking | | MT-LT |

*ST* short term (2010–2015), *MT* medium term (2015–2030), *LT* long term (2030–2050)

two other, advanced routes to iron. The electric arc furnace (EAF) is used to produce secondary steel from scrap.

In China, the energy consumption per ton of steel has declined from 1.43 to 0.52 toe between 1980 and 2005 [174]. Integrated steel plants have a specific primary energy consumption ranging from 19 to 40 GJ/t of steel [175], with minimills that use scrap steel being more efficient. Technology options for reducing energy use and $CO_2$ emissions in the iron and steel industry are tabulated in *Table 24.7* below, reproduced from [172].

## Aluminum

Worldwide primary aluminum production is projected to increase from 23 to 38 million tons by 2020 [175]. The primary aluminum [176] production, starting from bauxite via electrolysis (Hall–Héroult process), is a very energy-intensive process, contributing 1% of total anthropogenic greenhouse gas emissions in 1995 with about 364 million tons per year $CO_2$-equivalent [175].

Secondary aluminum production [177] consumes approximately 5% of the energy needed for primary production. Existing and potential future processes for bauxite processing are reviewed in [178]. Technology options for reducing energy use and $CO_2$ emissions in primary aluminum are summarized in the following *Table 24.8*, reproduced from [174].

## Other Primary Metals

Generally, one can distinguish between pyrometallurgical and hydrometallurgical processes. The ore content of a deposit influences energy efficiency as the chosen process does. The energy demand for comminution is described in [179]. Energy efficiency of a lead

**Table 24.8**

**Potential technologies to make energy-intensive production processes more efficient [172] (From IEA, DOE, AISI, Aluminum Association, Korean Energy Institute)**

| Technology option | Description | Time frame |
|---|---|---|
| Wetted, drained cathode technology | | MT-LT |
| Alternative cell concepts | Combines inert anode, drained cathodes | LT |
| Carbothermic and kaolinite reduction process on commercial scale | Alternatives to the Hall–Hérault process | LT |

*MT* medium term (2015–2030), *LT* long term (2030–2050)

smelter is discussed in [180], and energy efficiency of copper and magnesium production in [181] and [182], respectively. Processes for the production of steel, aluminum, copper, lead, and zinc are reviewed from an energy-perspective in [183]. Sintering processes and their energy efficiencies are discussed in [184] for one system, and scale-up in metallurgy in general in [170].

## Pulp and Paper

The pulp and paper (P&P) industry is a very energy-intensive one.

Pulp is being produced from wood by the Kraft process, with electricity as additional input and output, plus steam as an output. An efficient Kraft pulp mill can be a net exporter of heat and electricity [185].

Industry practice shows that in the past, most energy-efficiency measures were limited to low-investment, high-return projects, with typically 5% energy savings with a 1-year payback time [186], with a lot of potential still untapped into.

In current paper mills, steam savings of up to 30% are deemed feasible [187–191]. Energy efficiency savings can be obtained from the use of different fuels, which are typically wood, bunker oil, and black liquor [186], the latter being a by-product of the transformation of wood chips into pulp. Typical energy efficiencies in the industry for bark combustion are 67% (based on the higher heating value) and 80% for bunker oil combustion, respectively [186].

In [185], the utilization options for excess steam and heat at Kraft pulp mills are studied. Traditional ways are increased electricity production and district heating, whereas increased sales of biomass as bark and/or extracted lignin and carbon capture and storage (CCS) are new pathways.

There is a trend toward additional products, complementing the traditional pulp and paper output, by biofuels, pellets, lignin, carbon fibers, and other specialty chemicals [185] from pulp and paper plants.

In [186], the economics of *trigeneration* in a Kraft pulp mill are discussed. In trigeneration, pulp production, waste-heat upgrading, and power production are

**Table 24.9**

**Potential technologies to make energy-intensive production processes more efficient [172] (From IEA, DOE, AISI, Aluminum Association, Korean Energy Institute)**

| Technology option | Description | Time frame |
|---|---|---|
| Black liquor gasification | In demonstration, R&D; commercially available 2030; 15–23% gain | MT-LT |
| Efficient drying technology | R&D now; commercial demo: 2015–2030; commercial: 2030 onward | MT-LT |

*MT* medium term (2015–2030), *LT* long term (2030–2050)

simultaneously carried out (compare *polygeneration*). Absorption heat pumps (AHP) can be used to cool waste-heat streams and to extract energy from them. Technology options for reducing energy use and $CO_2$ emissions in the paper and paperboard industry, reprinted from [172], are summarized here in *Table 24.9*. Recycling is another option to increase energy efficiency of paper products. For details on energy efficiency options in the pulp and paper industry, see [192].

## Cement

The cement industry, already 15 years ago, exceeded 1.5 billion tons of annual output, making it a huge consumer of energy. For cement production, first clinker has to be made, which is then blended with approximately 5–70% additives such as gypsum and fly ash to yield cement. This first step is the most energy-intensive one. Limestone ($CaCO_3$) is burnt with silicon oxides, aluminum oxides and iron oxides. There is a wet process and a dry process, the latter one being more energy efficient. As cement plants [193] consume significant amounts of energy, approximately 4 GJ/t of cement produced [194], energy efficiency programs have been extensively applied to various plants [67, 195–198]. For each t of cement, approximately 0.5 t of $CO_2$ are generated [22].

In [67], potentials for energy efficiency improvements in the US cement industry are discussed, and in [199], those for China. $CO_2$ and energy intensity reductions in cement production can be achieved by

- Modification of the product composition (less clinker)
- Use of alternative cements (e.g., mineral polymers)
- Improving the energy efficiency of the process and process equipment
- Introduction of a different process (e.g., change from wet to dry process)
- Replacement of high carbon fossil fuels by low-carbon fossil fuels

A trend in the cement industry is the use of waste fuels such as tires. Recommendations on energy efficiency and cost-saving opportunities for the cement industry can be found in [200].

## Glass Production

Glass is a ubiquitous material that comes as sheet glass (produced in the float glass process), hollow glass (for glass containers), automotive glass, optical and other glasses such as glass fiber and glass wool. Its production is an energy-intensive process. According to [302], 74% of production costs are typically raw materials, fuels, and electricity. Recycling of glass offers a good way of increasing energy efficiency. One recycled bottle can save approximately 0.1 kWh [303]. In [304], best practices for energy efficiency improvements in the glass industry are provided. A detailed treatise of energy efficiency potentials in the American glass industry can be found in [305].

## Petroleum Refining

In a petroleum refinery (oil refinery) [201], crude oil is processed into various petroleum products such as naphtha, gasoline, diesel, and liquefied petroleum gas (LPG). Refineries are complex, chemical plants that are usually highly integrated. Crackers, for instance, can produce lightweight hydrocarbons as basic feedstock for the petrochemical industry (see also below).

Energy efficiency in a petroleum refinery can be tackled from various angles. Like in industry in general, there is usually optimization potential in cogeneration, steam systems, heat transfer systems and motors (see also [202–208] for details reported in the literature). Reference [209] estimated the energy savings potential for refineries to be around 15%.

The determination of the energy efficiency of a certain process is a somewhat tricky task as it depends on boundary limits to be drawn. Reference [210] attempts to allocate $CO_2$ emissions in petroleum refineries to various petroleum products. One aspect of the petrochemical and chemical industry in general that has to be noted here with respect to energy efficiency is that the energy contained in the feedstock is partly converted to heat and power, but also remains in the final products to some extent, providing potentials for recycling at the end of the various materials' lifetimes (feedstock recycling or thermal recycling). Recommendations on energy efficiency and cost-saving opportunities in refineries can be found in [211].

## Petrochemicals

Petrochemicals are products derived from petroleum [212] other than fuels for combustion. The petrochemical industry consumes approximately 8% of total oil production for the manufacture of various products [70], ranging from plastics, rubbers, and solvents to various fine chemicals. Two important upstream processes are *cracking* (fluid catalytic cracking, steam cracking) for the production of olefins such as ethylene and propylene, and *reforming* (catalytic reforming) for the production of aromatics.

Worldwide, more than $10^7$ t of propylene, $6.5 \times 10^6$ t of ethylene and $7 \times 10^6$ t of aromatics are produced per year. From these primary petrochemicals, to which also

**Table 24.10**

**Potential technologies to make energy-intensive production processes more efficient [172] (From IEA, DOE, AISI, Aluminum Association, Korean Energy Institute)**

| Technology option | Description | Time frame |
|---|---|---|
| High-temperature furnaces | Able to withstand more than 1,100°C | MT-LT |
| Gas-turbine integration | Higher-temperature CHP for cracking furnace | MT-LT |
| Advanced distillation columns | | MT-LT |
| Combined refrigeration plants | | MT-LT |
| Biomass-based system options | Feedstock substitution | LT |

*MT* medium term (2015–2030), *LT* long term (2030–2050)

synthesis gas can be counted, a wide range of chemical products is made. Energy efficiencies of a steam cracker are reported in [213] and [214]. Naphtha crackers are estimated to consume 31.5 GJ/t of energy [215].

The gross energy requirement (GER) for major petrochemical products such as ethylene, propylene, butadiene, and benzene is reviewed in [209]. Technology options for reducing energy use and $CO_2$ emissions for petrochemicals are shown here in *Table 24.10*, from [174]. Below, details on some petrochemical products with respect to energy efficiency are reviewed.

## Polymers

The polymer industry has ramped up plastics production between 1950 and 2007 from 1.5 to 260 million tons [216] worldwide, which corresponds to an annual growth rate of more than 9%, making plastics ubiquitous and versatile construction materials. Polyolefins are the most common plastics, with polyethylene (PE) and polypropylene (PP) accounting for the largest fraction, followed by polyvinylchloride (PVC), polystyrene (PS) and expanded polystyrene (EPS), polyethyleneterephthalate (PET), polyurethane (PUR), and others, e.g., engineering plastics such as polycarbonate (PC).

Polymers can be produced with different technologies, ranging from radical reactions (high-temperature and high-pressure processes such as for high density polyethylene [HDPE]) to catalytic processes (at more moderate conditions), which show varying energy efficiencies.

The gross energy requirements for the production of low-density polyethylene (LDPE), PP, PS, and PVC are 69.8, 61.6, 81.5, and 55.7 GJ/t, respectively [209]. Plastic production uses 8% of the world's oil production, 4% as feedstock and 4% during manufacture [217].

Cogeneration and heat recovery in polymerization processes are discussed in [218]. In Europe, the recycling rate of plastics has reached 51.3% (21.3% recycling and 30.0% energy recovery, i.e., combustion) [216]. Reference [209] investigated potential energy savings in the production of plastics. That study found that the technical potential for

energy efficiency savings varies from 12% for PE to 25% for PVC. Further information on energy use in plastics production can be found in [219]. Alternative feedstocks, biopolymers, and feedstock recycling [220] are emerging trends in the industry with impact on energy efficiency.

## Chemical Industry

The chemical industry uses crude oil, natural gas, and coal, apart from electricity, both as raw materials and as fuels to produce more than 50,000 different products. More than half of the energy used by the chemical industry is processed as feedstock, which means that it is transformed into various products such as chemicals or polymers. Most energy is consumed by the production of a few small, intermediate compounds. In the chemical industry, energy costs account for 10–15% of total manufacturing costs [221]. For some processes such as electrolysis, energy costs can exceed 50% of production costs. The DOE estimates potential energy savings within the chemical industry to be approximately 20%.

Strategies to improve energy efficiency in the chemical industry are process improvements, cogeneration, integration, and the introduction of energy management systems (EMS). Integration means that rather than producing a single chemical, a production location should strive to use its feedstock to make the desired final product, while utilizing by-products as well. If several production steps, such as crude oil distillation, cracking, and polymerization, can be done in one location, costly and wasteful transportation and storage steps can be avoided (compare the German concept of an integrated chemical complex, the "Verbund." At the largest chemical Verbund site, BASF's, Ludwigshafen, synergies amount to €500 million per year, €150 million out of which are attributed to energy savings [70]).

Process design is also an important consideration for energy efficiency as different unit operations [222] have varying energy demands. In [215], energy use and energy intensity of the US chemical industry are analyzed. A general review on sustainability and energy efficiency in the chemical industry is provided by [223]. Below, some details on various products of the chemical and process industries with respect to energy efficiency are compiled. Actual energy consumption values for the production of chemicals are significantly higher than the theoretical demand stipulated by thermodynamics. A "clean-sheet redesign," not considering cost-effectiveness, would offer a potential for energy savings in chemicals production of up to 95% [9, 65]. Catalysts, as they lower the activation energy, can generally increase energy efficiency, particularly enzymatic catalysts for several particular reactions. *Process intensification* and *polygeneration* are two emerging technologies that could reduce energy demand in the chemical industry. By process intensification [224], more compact and efficient plants can be designed. Polygeneration using natural resources is detailed in [225]. An overview on energy efficiency in the chemical industry is provided in [226–229]. *Green chemistry* is discussed in [230, 231].

### Ammonia

Ammonia is one of the inorganic chemicals with the highest yearly production volume. Its global consumption is in excess of $10^7$ t. $NH_3$ is the precursor to most industrially produced nitrogen-containing compounds. More than 80% of ammonia is processed to fertilizers. Ammonia production consumes more than 1% of all man-made power [232]. $CO_2$ emissions in ammonia production are estimated to be 1.58 t for each ton of product [22]. Energy consumption is quoted as 39.3 GJ/t for feedstock (natural gas) plus 140 kWh/t electricity, totaling to 40.9 GJ/t (based on higher heating value, corresponding to 37.1 GJ/t based on lower heating value) [215]. Without considering the natural gas, the primary energy consumption for ammonia production is 16.7 GJ/t [215].

For energy efficiency studies and improvement potentials in ammonia production, see [233] and [234]. The use of ammonia as a fuel is described in [235]. The specific energy consumption for the production of urea is estimated at 2.8 GJ/t (1994) [215].

### Fertilizers

Nitrogen-bearing fertilizer production is a very energy-intensive industry. Ammonia is the most important intermediate chemical compound here (see also above). *Table 24.11* shows the energy use and emission intensity for the production of various fertilizer components, reprinted from [239].

An early review on energy efficiency in fertilizer production is provided by [237]. Energy efficiency in the fertilizer industry is reviewed in [237–241].

### Methanol

Methanol can be produced by steam reforming from methane [242]. It can also be obtained from coal [243] and various biomass products [244] such as sugar cane. Methanol has seen increased interest for its use in

- Direct methanol fuel cells [245]
- Fuel for combustion engines [246]
- Feedstock for the chemical industry [247]

**Table 24.11**

**Energy requirements to manufacture fertilizer components plus associated $CO_2$ emissions [236]**

| Component | Energy use [MJ/kg] | Emissions [kg $CO_2$/MJ] |
|---|---|---|
| N | 65 | 0.05 |
| P | 15 | 0.06 |
| K | 10 | 0.06 |
| S | 5 | 0.06 |
| Lime | 0.6 | 0.72 |

In 1994, the specific energy consumption for the production of methanol was 38.4 GJ/t (based on higher heating value) [215].

### Industrial Gases

A wide variety of gases is industrially produced and sold in compressed or liquid state. Apart from air, oxygen and nitrogen are amongst the most commonly used industrial gases [248], others being argon (welding), carbon dioxide, and methane. Oxygen and nitrogen have traditionally been produced through cryogenic air separation, where air is cooled and pressurized until it becomes a liquid with the various gases being extracted through fractionated distillation. The associated energy consumption is estimated to be 1.8–2.0 GJ/t of oxygen or nitrogen [215].

Other energy-efficient technologies such as pressure swing adsorption (PSA) [249] and membrane separation [250] are increasingly used. An article on energy efficiency gains in gas production (thermal gasification) is given by [251].

### Chlorine

Chlorine is produced through electrolysis of a salt solution (brine), which is an energy-intensive process requiring between 3,065 and 3,960 kWh/t [215]. The coproducts caustic soda (sodium hydroxide, NaOH) and hydrogen gas ($H_2$) are obtained, with the major markets for chlorine being PVC (polyvinylchloride) manufacturing, inorganic chemicals, propylene oxide, water treatment, and organic chemicals. The chlorine industry is reviewed in [252]. Technology options for reducing energy use and $CO_2$ emissions in chlor-alkali manufacturing are summarized from [172] in the *Table 24.12* below.

### Hydrogen

Hydrogen is regarded as an interesting option as transportation fuel and as storage medium for electricity, being produced from renewable resources. The "Hydrogen Economy" [253] is often seen as a straightforward solution to many issues around pollution and global warming. Despite all the potential that lies in the technical exploitation of hydrogen, it needs to be borne in mind that the hydrogen – as clean as it is as such – has to be produced. Hydrogen from nuclear power is treated in [254] and [255]. It is the overall

**Table 24.12**

**Potential technologies to make energy-intensive production processes more efficient [172] (From IEA, DOE, AISI, Aluminum Association, Korean Energy Institute)**

| Technology option | Description | Time frame |
|---|---|---|
| Convert mercury-process and diaphragm-process plants to membrane technology | Combined electrolytic cell with a fuel cell, using hydrogen by-product | MT-LT |

*MT* medium term (2015–2030), *LT* long term (2030–2050)

**Table 24.13**
**Pharmaceutical industry and energy use [95]**

| Area | Distribution of energy use |
|---|---|
| R&D | 30% |
| Offices | 10% |
| Production of bulk pharmaceutical substances | 35% |
| Formulation, packaging, and filling | 15% |
| Warehouse | 5% |
| Miscellaneous | 5% |
| Total | 100% |

energy efficiency (system efficiency) that will determine whether hydrogen will be used on a large scale as energy carrier. For details, see [256].

### Pharmaceutical Industry

The US pharmaceutical industry has energy expenses of approximately $1 billion per year [95], which, being only a small fraction of total production costs, is still significant, given the fact that energy savings will translate into direct and predictable earnings. In the pharmaceutical industry, there are three overall stages:

- Research and development (R&D)
- Production of bulk pharmaceutical substances
- Formulation of the final products

*Table 24.13* shows the distribution of energy use [95] in this sector. Twenty-five percent of the total energy is used for plug loads and processes, 10% for lighting, and 65% for HVAC (heating, ventilation, and air conditioning). The biggest potential can hence be found in R&D and bulk manufacturing.

## Public Sector and Community Infrastructure

The public sector is another area where energy efficiency potential exists. Awareness of energy efficiency and conservation is a major topic. In a typical office, nearly 40% of the electricity consumption occurs after closing hours [257]. Government institutions can apply energy-efficient procurement and create awareness for energy savings. Public buildings (see also next section) offer energy efficiency increase potential, as does for instance the lighting infrastructure of public roads. *Desalination* plants are important in several parts of the world. Their energy efficiencies for different technologies are assessed in [258–262].

## Buildings

Buildings have a strong and long-lasting impact on global energy consumption because they are constructed for typically 50–100 years. In 2005, 39% of the total energy consumption in the USA stemmed from commercial and residential buildings [39]. They accounted for as much as 70% of total electricity consumption [39]. There is hence a huge potential for what is known as *green buildings*.

The residential sector in the USA is expected to account for 29% of the US energy consumption in 2020 [9], driven by population growth, larger homes and more electric and electronic gadgets in private households. The specific energy use for heating of buildings, a major parameter for their energy efficiency, is given in kWh/($m^2$ year).

Key determinants for energy efficiency of buildings are

- Location and surroundings
- Insulation
- Heating technology

Sealing of ducts, basement insulation and improved heating equipment are seen as major efficiency opportunities in private homes in the USA [9]. *Heat pumps* are particularly energy efficient. There are three types of heat pumps: air-to-air, water source, and ground source. Ground source heat pumps typically use four times less electrical energy than direct electrical heaters. Deviations in energy efficiency from the design requirements to actual performance may come from

- Errors in the design
- Errors in the construction
- Incorrect operation
- Lack of maintenance
- Changed use of the building

Various tools, such as an *energy survey* or an *energy audit*, can help uncover efficiency potentials. On average, heating and cooling account for almost half of a typical utility bill. Drafty rooms can be improved by checking windows and doors. The HVAC (heating, ventilation, air conditioning) system often offers potential for improvement, and so does the lighting. Compact fluorescent lights (CFL) are more efficient than electric bulbs.

*Passive buildings* [265] and *zero net energy (ZNE) buildings* [263, 264] are more energy efficient than traditional ones. For ZNE buildings, *embodied energy* [116] can be considered. This is the quantity of energy required to manufacture and transport the materials utilized for their construction.

According to [116], the total embodied energy of load bearing masonry buildings can be reduced by 50% when energy-efficient/alternative building materials are used.

*Landscaping* around private homes can also bring measurable energy savings. Carefully positioned trees can save up to 25% of a household's energy consumption for heating and cooling. They can, apart from giving a nice appearance, provide shade and shelter from wind. Payback times for such planting measures can be as low as several years [266].

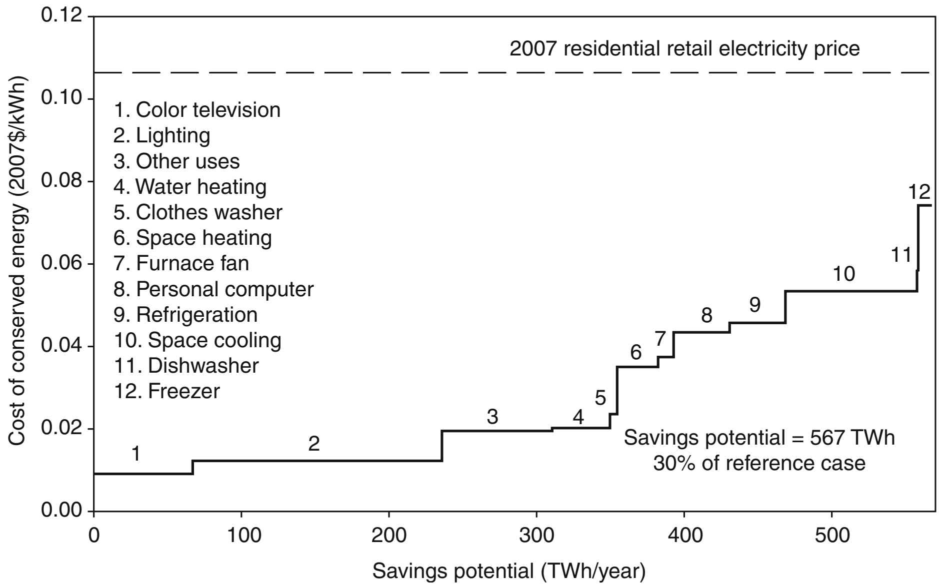



**Fig. 24.10**
**Residential electricity savings potential in the year 2030 (Reprinted with permission from [268])**

*Micro-generation* for individual houses is another interesting technology option for the energy-savy. A small combined heat and power (CHP) system to produce electricity and heat for a community or a single household is known as micro-generation [267]. The most promising technologies are Stirling engines and fuel cells in a size range of approximately 1–10 $kW_e$. Total efficiencies can be typically 80–88% [267].

It is estimated that in US buildings, one third of the total energy consumption can be saved at a cost of 2.7 $c/kWh [268], see also for natural gas savings there. *Figure 24.10* below shows the electricity savings potential for the residential, and *Fig. 24.11* the same scenario for the commercial sector.

It can be seen from *Fig. 24.10* that in the residential area, a huge potential exists for TV sets, lighting, and space cooling, with freezers already being rather optimized. *Figure 24.11* below takes a look at the commercial sector.

In the commercial sector, space cooling and lighting offer large potential, with the most cost-effective opportunities residing in space heating and ventilation. Energy efficiency in the residential area is covered in [269]. A guide on energy efficiency for home owners can be found in [270].

## Appliances

Appliances are a collection of electrically powered devices, which can be found in nearly every household. They account for approximately 20% of a typical household's energy

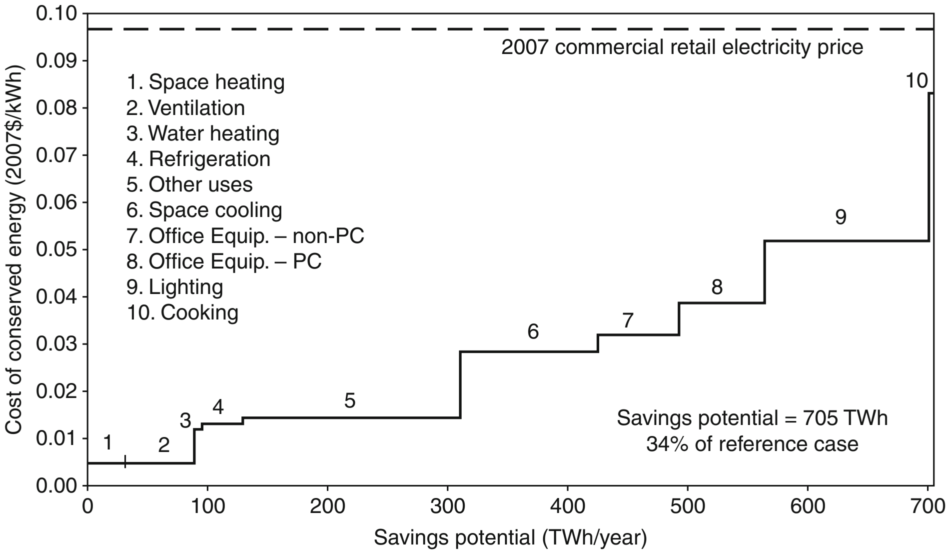



**Fig. 24.11**
**Commercial electricity savings potential in the year 2030 (Reprinted with permission from [268])**

consumption, with refrigerators, washing machines, and dryers at the top of the consumption list. A "cheap" device can become very costly over its entire lifetime of up to 10 or 20 years (see TCO concept above).

In 1978, California took a leading national role in the USA by establishing the first building and appliance standards in the country. Nearly 85% of all dishwashers in California are Energy Star® compliant (see later), and 50% of refrigerators and washing machines conform to these standards too. What is even more impressive, however, is that this increase in market share occurred within no more than 7 years, see *Fig. 24.12*, reprinted with permission from [271].

Typical renewal cycles of appliances in industrialized countries, here the USA, are shown in *Fig. 24.13* below, reprinted from [272]. Modern appliances consume significantly less energy than older ones.

## Lighting

Lighting has played a large part in the public discussion on energy efficiency. As traditional incandescent bulbs, which have an efficiency on the order of 1% to produce light, are being phased out in many countries, mild panic-buying could be observed in 2009 [273]. Some consumers oppose the compact fluorescent lights (CFL), which typically cost four times as much as traditional bulbs. The fact that their energy consumption is one fifth and that payback times are typically short has not convinced all consumers (yet). There are

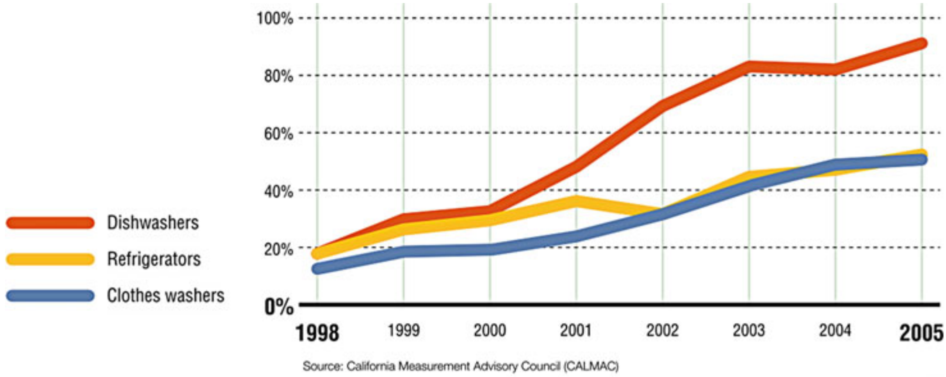
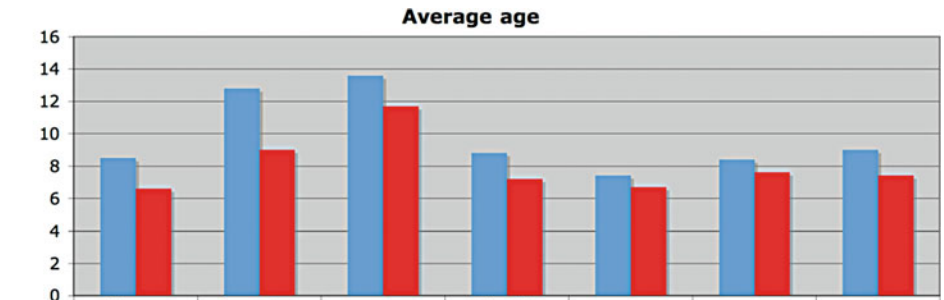



**Fig. 24.12**
**Market share of Energy Star® appliances in California (Reprinted with permission from [271])**




| | Primary refrigerators | Secondary refrigerators | Freezers | Hot water heaters | Washers | Dryers | Dishwashers |
|---|---|---|---|---|---|---|---|
| 2000 | 8.5 | 12.8 | 13.6 | 8.8 | 7.4 | 8.4 | 9 |
| 2005 | 6.6 | 9 | 11.7 | 7.2 | 6.7 | 7.6 | 7.4 |

**Fig. 24.13**
**Appliance renewal cycles (Reprinted with permission from [272])**

reservations against the hue of the CFL's light. CFL that work in dimmers tend to cost more than standard CFL. In [274], a lifecycle analysis of CFL is made.

## Consumers

Up to two third of household energy use is for space heating, water heating, and refrigeration [9], with lighting playing a lesser role. Another significant share is held by the "plug load." "Plug load" is a collective term for electrical devices and small appliances. These are virtually hundreds of small devices in private homes, consuming electricity. The biggest shares are held by TV sets (22%), DVD players (5%), PCs (5%), and microwave ovens (3%) [9]. *Standby power consumption* is a huge energy waster. In Japan, the annual per-household standby electricity consumption could be reduced from 437 to 308 kWh

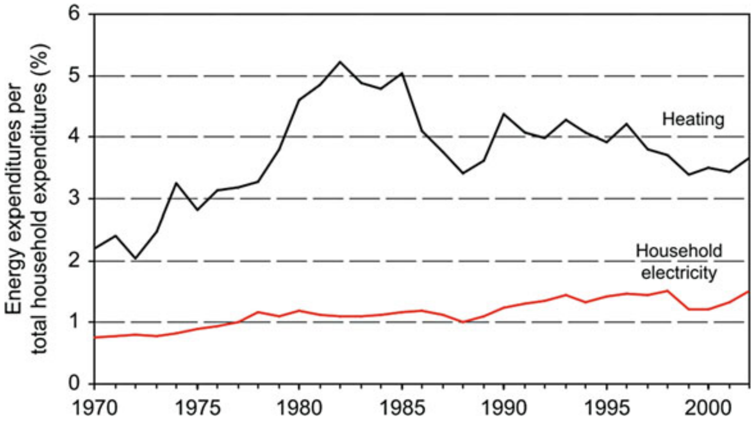



**Fig. 24.14**
**Annual average of expenditures of households on energy for heating and electricity (Reprinted with permission from Elsevier from [75])**

from 2002 to 2005 [9]. *Figure 24.14* shows typical energy expenditures for Swedish households, reproduced from [75].

It is assumed that with a tripling of energy prices, energy use of private households would decrease by 30% [75]. Energy-consciousness of consumers has increased over the last years, partly induced by various initiatives such as Energy Star®, see also below.

### Tips and Tricks for Consumers

There are plenty of tips and tricks in various organizations' and authorities' brochures and internet pages for consumers on how to lower their utility bills. Most of them are commonsense, but it is worthwhile to take a look at them to capture some fast savings. Here are a few examples of often unused potential in private homes:

- The temperature of the refrigerator is too low.
- The refrigerator is positioned in a confined space.
- The washing machine is operated half-empty with too warm water temperature.
- Open food is stored in refrigerators (liquids need to be covered, and food should be wrapped to avoid moisture release).
- Untight windows.
- Time is not considered (peak electricity is most costly).

## Initiatives for Energy Efficiency

Energy efficiency improvements do not come "naturally," at least not at the desired speed. In order to overcome the known barriers toward energy efficiency, which were outlined

above in this chapter, government action can help. Numerous programs and initiatives to educate people about and to promote energy efficiency have been started by governments, NGOs (nongovernmental organizations), NPOs (nonprofit organizations), for-profit entities and visionary individuals such as business owners and public celebrities. One such initiative is Energy Star®.

Energy Star® label is used to identify energy-efficient appliances. It was initiated by the DOE (US Department of Energy) and the EPA (US Environmental Protection Agency). Products with the Energy Star® label usually exceed minimum efficiency standards by a substantial amount. More information on Energy Star® can be found at [275] and [276]. The impact of agreements on energy efficiency is reviewed in [4].

## Other Aspects

There are countless areas for hidden or for indirect energy efficiency improvements, some of which are being touched upon here.

Advanced *packaging*, for instance, can save substantial amounts of materials to achieve the same level of goods protection. Lightweight packaging will make transportation over long distances more energy efficient. One example is the replacement of bulky glass bottles by composite containers of (recycled) cardboard and plastics.

In *information technology* (IT), there is often an untapped potential for energy savings and efficiency improvements. Anyone who has witnessed the large air-conditioning systems for server rooms will immediately see the potential offered by what has become known as "green computing." More details can be found in [277] and [278].

The *service sector* can also contribute to more energy efficiency. *Electronic banking, video telephony* and *teleconferencing* [279], *telecommuting* [280, 281], and *fleet management* [282] are just a few examples where energy for traveling can be economized.

In general, shifting employment and economic activity from manufacturing to the services sector saves energy and cuts greenhouse gas emissions because the services sector is much lower in energy intensity. Energy efficiency potentials in hospitals are discussed in [283]. Energy efficiency under extreme conditions is reviewed in [284].

## Energy Conservation

Being a broader term than energy efficiency, energy conservation is about using less energy, with a lower energy service being delivered. Sometimes, it is used synonymously with energy efficiency. Energy saving is without doubt the quickest, most effective, and most cost-efficient way for reducing greenhouse gas emissions, as well as improving air quality, especially in developing countries and in densely populated areas. An example of energy conservation on a private level is, for instance, driving less with one's car. An organization can study its office lighting setup to remove costly over-illumination, for example. For more information on energy conservation, see [53, 285–290].

## Further Study and Reading

In this section, a few terms that are related to energy efficiency were compiled as a starting point for further exploration by the interested reader.

*Dematerialization*: By this expression, one can understand the decline of weight and "embedded energy" (cf. embodied energy) of materials in industrial end products over time, or, more broadly speaking, the absolute or relative reduction in the quantity of materials required to serve economic functions [291, 292]. On the one hand, one can observe a decline in weight of certain goods such as PCs, and on the other hand, people tend to use more materials as their comfort level increases (e.g., larger homes, larger cars). Trends of dematerialization are reviewed in [291]. A similar term is *ephemeralization*, which was coined by R. Buckminster Fuller. It is the ability of technological advancement to do "*more and more with less and less until eventually you can do everything with nothing*" [293].

*Industrial ecology*: Being defined as a "*systems-based, multidisciplinary discourse that seeks to understand emergent behavior of complex integrated human/natural systems*" [294], industrial ecology strives at sustainability and eco-efficiency. More information on the topic can be found in [295].

*Eco-efficiency*: According to the World Business Council for Sustainable Development (WBCSD), it is expressed as

- Reduction in the material intensity of goods or services
- Reduction in the energy intensity of goods or services
- Reduced dispersion of toxic materials
- Improved recyclability
- Maximum use of renewable resources
- Greater durability of products
- Increased service intensity of goods and services

More information can be found in [296].

*Water efficiency*: Water efficiency is closely linked to water conservation. It can be defined as the accomplishment of a function, task, process, or result with the minimal amount of water feasible. Effluent reuse is one important means of achieving water efficiency [297]. It is estimated that each $m^3$ of water utilized in the industrial and service sectors generates at least 200 times more wealth than it does in the agricultural sector [298]. This suggests that water-intensive production will be shifted from arid regions to those with more water (compare the shift of $CO_2$-intensive production to certain areas). Here, the concept of *virtual water* [299, 300] steps into place. Virtual water, also called *embedded water, embodied water*, or *hidden water*, refers to the water needed to manufacture a good or service.

Yearly individual water consumption is on the order of 1 $m^3$ for drinking, 100 $m^3$ for domestic use, and 1,000 $m^3$ embedded in food. This shows that the concept of virtual water is closely linked to water efficiency and ultimately to energy efficiency.

Other burning topics related to energy are the *affordability* of energy and *access to energy*, which are both not secured for a high number of people.

## Conclusions

This chapter has taken a look at energy efficiency in industry, transportation, the private sector, and other areas, exploring a topic of high relevance for climate change mitigation. Energy-use efficiency is the cheapest and easiest source of energy, with a huge unused potential. It is estimated that up to one third of the worldwide energy demand in 2050 can be saved by energy efficiency measures.

In this chapter, aspects of energy efficiency from various sectors were presented, spanning historic data, current levels, and future trends. An emphasis is placed on providing brief information and references on how energy efficiency improvements can be realized.

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